Evaluating the utilisation of industrial excess heat from an energy systems perspective

Igor Cruz

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ABSTRACT

Sweden aims to achieve climate neutrality by 2045. The need to immediately reduce greenhouse gas emissions in order to achieve climate targets affects industry directly. The pulp and paper sector is responsible for more than 50% of industrial energy use in Sweden. Increased energy efficiency is expected to contribute significantly to the reduction of primary energy use. The recovery and utilisation of industrial excess heat (IEH) has been identified as an important potential contribution to energy efficiency in industry. Previous research based on top-down studies has estimated the availability of IEH for entire sectors, and bottom-up results for many case studies are available. While top-down studies lack detailed information on the profile of the excess heat available, bottom-up studies have limited coverage. Detailed information about excess heat amounts and temperature levels is required for the assessment of the potential of the various heat recovery technologies that are available.

The aim of this thesis is to present, in a series of steps, methods to systematically analyse an industrial process to obtain a detailed profile of the excess heat available under various process conditions, to aggregate results that can be generalised to whole industrial sectors, and to obtain IEH recovery potentials using different technologies. The assessment of the utilisation options for IEH recovery is complemented with an analysis of system aspects that could affect profitability and global greenhouse gas (GHG) emissions. An energy-targeting procedure combined with optimisation has been applied to six case studies of kraft pulp and paper mills in Sweden. This method obtained IEH profiles that were used in a regression analysis to estimate the IEH availability and electricity generation potentials from low and medium temperature IEH using organic Rankine cycles (ORC). A comparison of profitability and global GHG emissions between ORC electricity generation using IEH and small-scale combined heat and electricity (CHP) production is presented for three energy markets.

The results show that there is a potential to increase electricity generation from low and medium temperature IEH by 7–9% in the kraft mills in Sweden, depending on the level of process integration considered. The utilisation of low and medium temperature IEH for electricity generation has the potential to reduce global GHG emissions in all the energy-market scenarios considered, but if biomass is considered a limited resource, district heating (DH) deliveries can achieve higher global GHG reductions. ORC electricity generation from low and medium temperature IEH is economically viable and showed overall better profitability and GHG emissions reductions than small-scale CHP using ORCs. The economic feasibility of ORC electricity generation is less affected by external conditions and uncertainties than direct DH deliveries.

SAMMANFATTNING

Sverige siktar på att uppnå klimatneutralitet till 2045. Behovet av att omedelbart minska utsläppen av växthusgaser för att nå klimatmålen påverkar industrin direkt. Massa- och papperssektorn står för mer än 50% av den industriella energianvändningen i Sverige. Ökad energieffektivitet förväntas i hög grad bidra till att minska primärenergianvändningen. Återvinning och utnyttjande av industriell överskottsvärme (IÖV) har identifierats som ett betydande potentiellt bidrag till energieffektivitet i industrin. Tidigare forskning baserad på top-down studier har uppskattat tillgängligheten av IÖV för hela sektorer eller regioner, och bottom-up resultat för många fallstudier finns tillgängliga. Medan top-down studier saknar detaljerad information om profilen för tillgänglig överskottsvärme, har bottom-up studier begränsad täckning och precision. Detaljerad information om överskottsvärmemängder och temperaturnivåer krävs för att bedöma potentialen hos flera värmeåtervinningstekniker.

Denna avhandling syftar till att i en serie steg presentera metoder för att systematiskt analysera en industriell process för att erhålla en detaljerad profil av tillgänglig överskottsvärme under olika processförhållanden, för att aggregera resultat som kan generaliseras för hela industrisektorer, och att erhålla återvinningspotentialer för industriell överskottsvärme med hjälp av olika teknologier. Bedömningen av olika möjligheter att använda industriell överskottsvärme kompletteras med en analys av systemaspekter som kan påverka lönsamhet och globala växthusgasutsläpp. Ett energimålsförfarande kombinerat med optimering har tillämpats på sex fallstudier av massa- och pappersbruk i Sverige, med produktion baserat på sulfatmassa. Med denna metod erhålls IÖV-profiler som används i en regressionsanalys för att uppskatta tillgängligheten av IÖV och potentialen för elproduktion från låg- och medeltempererad IÖV med organiska Rankine-cykler (ORC). En jämförelse av lönsamhet och globala växthusgasutsläpp mellan elproduktion med ORC, där IÖV utgör grunden, och småskalig kombinerad värme och el (KVV) produktion presenteras för tre energimarknader.

Resultaten visar en potential att öka elproduktionen från låg- och medeltempererad IÖV med 7% till 9% i sulfatmassabruken i Sverige, beroende på graden av processintegration som beaktas. Användningen av låg- och medeltempererad IÖV för elproduktion kan potentiellt minska de globala växthusgasutsläppen i alla övervägda energimarknadsscenarier. Om biomassa betraktas som en begränsad resurs, kan emellertid direkta fjärrvärmeleveranser uppnå högre globala minskningar av växthusgaser. ORC-elproduktion från låg- och medeltempererad IÖV är ekonomiskt lönsam och visade överlag bättre lönsamhet och minskade växthusgasutsläpp än småskalig ORC-kraftvärme. Den ekonomiska genomförbarheten av ORC-elproduktion påverkas mindre av yttre förhållanden och osäkerheter än fjärrvärmeleveranser.

List of papers

This thesis is based on the work described in the papers listed here. The papers are appended at the end of the thesis.

1. Svensson, E., Morandin, M., Cruz, I., Harvey, S. Availability of excess heat from the Swedish Kraft pulping industry. In *Proceedings of the International Sustainable Energy Conference on Renewable Heating and Cooling in Integrated Urban and Industrial Energy Systems*, Graz, Austria, 23 March 2018; pp. 697–706.
2. Cruz, I., Wallén, M., Svensson, E., Harvey, S. Electricity generation from low and medium temperature industrial excess heat in the kraft pulp and paper industry. *Energies*. 2021; 14(24):8499. <https://doi.org/10.3390/en14248499>
3. Cruz, I., Johansson, M. T., Wren, J. Assessment of the potential for small-scale CHP production using organic Rankine cycle (ORC) systems in different geographical contexts: GHG emissions impact and economic feasibility. Submitted for publication.

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Abbreviations

4DH	fourth-generation district heating	IPCC	Intergovernmental Panel on Climate Change
ADt	air-dry tonne	LCC	lifecycle costs
BR	Brazil	NGCC	natural gas combined cycle
CCS	carbon capture and sequestration	NPV	net present value
CHP	combined heat and power	ORC	organic Rankine cycle
CO₂	carbon dioxide	PCM	phase change materials
CRF	capital recovery factor	PV	photovoltaic
DH	district heating	SD	sustainable development
DR	delayed recovery	SE	Sweden
EED	energy efficiency directive	SEG	Smart Export Guarantee
ENPAC	Energy Price and Carbon Balance Scenarios	SP	stated policies
ETS	emissions trading scheme	TEG	thermoelectric generators
EU	European Union	TPV	thermophotovoltaic generators
EUR	Euro	UK	United Kingdom
FRAM	Future Resource Adapted Pulp Mill	USD	United States dollar
GCC	grand composite curve	WEO	World Energy Outlook
GHG	greenhouse gas	WF	weight factor
HOB	heat-only boiler	XHT	excess heat-temperature
IEA	International Energy Agency		
IEH	industrial excess heat		
IETS	Industrial Energy-related Technologies and Systems		

Table of Contents

1	Introduction	1
1.1	Aim and research questions	2
1.2	Research journey	3
1.3	Overview of papers included and co-author statements	3
2	Theoretical background	5
2.1	Concepts and definitions of industrial excess heat	5
2.2	Estimations of excess heat availability	6
2.3	Temperature intervals in excess heat studies	7
2.4	Technologies for the conversion of industrial excess heat into electricity	9
2.4.1	Organic Rankine cycle (ORC)	9
2.4.2	Kalina Cycles	10
2.4.3	Stirling engines	10
2.4.4	Phase Change Materials (PCMs)	10
2.4.5	Thermoelectric generator (TEG)	11
2.4.6	Thermophotovoltaic generator (TPV)	11
2.4.7	Comparison of the excess heat conversion technologies	12
3	Cases studied	13
3.1	The pulp and paper industry in Sweden	13
3.2	Countries and system configurations studied	15
3.2.1	Sweden	15
3.2.2	The United Kingdom	16
3.2.3	Brazil	16
4	Methods	19
4.1	Availability of industrial excess heat and calculating electricity generation potentials	20
4.1.1	Thermal stream data from case studies and sectorial public database ..	20
4.1.2	Targeting conventional electricity production with steam Rankine cycles ..	21
4.1.3	Excess heat-temperature (XHT) signatures for case studies	22
4.1.4	Regression analysis – XHT signatures for all Swedish kraft mills	25
4.1.5	Estimation of new electricity generation potentials from low and medium temperature excess heat using organic Rankine cycles	25
4.1.6	Estimation of DH delivery potentials	28
4.2	Scenarios and CO ₂ emissions balance	29
4.2.1	Energy-market scenarios	31
4.3	Economic evaluation	34

4.3.1	District heating deliveries	34
4.3.2	Organic Rankine cycle equipment.....	35
5	Results and analysis	37
5.1	Excess heat availability and excess heat temperature signatures	37
5.2	Regression analysis for excess heat availability	40
5.3	Low and medium temperature electricity generation and DH deliveries for the case studies	41
5.4	Regression analysis for low and medium temperature electricity generation ..	43
5.5	CO ₂ emissions balances	44
5.6	Economic analysis	46
5.6.1	Sensitivity analysis	47
5.7	Comparison of IEH recovery with small-scale ORC CHP.....	49
5.7.1	Economic feasibility of ORC technology in different applications and energy markets.....	49
5.7.2	Carbon dioxide emissions balances of ORC technology in different applications and energy markets.....	52
6	Discussion	55
6.1	Heat integration and excess heat availability.....	55
6.2	Electricity generation from low and medium temperature IEH	56
6.3	CO ₂ emissions balances and economic analysis.....	57
7	Conclusions	59
8	Further work	61
	References	63

1 Introduction

This chapter begins with the presentation of the background of the thesis and continues with the aim and research questions proposed. The chapter ends with an overview of the research journey and a description of the appended papers, and the contributions made by the author of this thesis.

Industrial, technological and economic development has led to an exponential increase in the demand for energy since the beginning of the 20th century, particularly after the 1950s. Due to their wide availability, relatively low cost and properties such as high energy density and easy storage and transportation, fossil fuels have met the majority of this increase in demand. The global primary energy use in 2019 was estimated at 173 340 TWh¹, of which oil (31% of total), coal (25%) and natural gas (23%) were still the three main primary energy sources [1,2]. The use of fossil fuels is the main source of anthropogenic greenhouse gas (GHG) emissions. The atmospheric concentration of carbon dioxide has increased by 40% compared to pre-industrial levels, and is directly related to climate change and global warming [3]. In 2018, the Intergovernmental Panel on Climate Change (IPCC) released a Special Report identifying the impacts of a global temperature increase of 1.5°C above pre-industrial levels [4], calling for immediate action to achieve accelerated reductions in GHG emissions in order to achieve net zero GHG emissions by 2050. Over the last three decades, the European Union (EU) has had a history of policy action related to climate change issues, energy supply and energy use. In its latest form, the European Commission's long-term climate strategy aims to achieve climate neutrality by 2050, with an intermediate target of at least a 55% reduction in emissions by 2030, compared to 1990 levels [5]. The current 2030 targets set by the Energy Efficiency Directive (EED) of at least a 32% share of renewable energy and a 32.5% increase in energy efficiency are under review, with suggestions to increase the target for the share of renewable energy to 65% or more, and to revise the target for energy efficiency [6–8]. In line with EU targets, the current Swedish Climate Act entered into force in January 2018 and aims to make Sweden carbon neutral by 2045, and to reduce GHG emissions by 63% (1990 baseline) by 2030 [9].

Achieving these targets requires a combination of measures. The International Energy Agency (IEA) has identified improved energy efficiency as the single biggest potential contribution to reducing final energy use in energy end-use sectors, achieving 60% of the savings compared to a scenario considering only current climate policies worldwide [10]. Half of these savings would take place within industry. However, to achieve the goals in

¹ This figure is based on the substitution method, correcting nuclear and renewable sources (except biomass) to the primary energy equivalent of utilising fossil fuels to meet an energy demand.

this scenario, a reduction in energy intensity of 3.6% per year until 2040 is required, compared to the reduction of 2.3% seen in 2018 in the EU [10].

Industrial excess heat (IEH) has been identified as a resource with the potential to contribute to meeting the climate and energy efficiency targets, and a relatively high amount of untapped potential remains unused [11]. In Sweden, IEH is currently responsible for 8.3% of the energy supply for district heating (DH) networks [12], and it is considered that the potential for increased use, including other uses such as electricity generation, is significant [13,14].

The utilisation of IEH reduces the demand for primary energy resources that would otherwise be needed for the production of heat or to supply other energy services [15,16]. The EED recognises some of these benefits of IEH use, especially when considering electricity production and DH [6]. Additionally, industries in several sectors are interested in increasing the use of their own excess heat, and to supply excess heat externally [17]. The recovery and use of IEH could provide a new revenue stream for companies, by using a resource that is currently wasted, thus increasing industrial competitiveness, and opening up opportunities for regional collaboration and industrial clusters [18].

Excess heat is an output quantity of an industrial process with no direct costs, and which rarely generates revenue. Thus, it is usually not measured in detail. There are different methods available for estimating excess heat, and these vary broadly in scope, coverage and level of detail [19,20]. A better understanding of the availability, potential uses and consequences for the energy systems of IEH use is relevant not only for individual process sites, but also within the broader context of regional and national energy systems.

1.1 Aim and research questions

The aim of this thesis is to analyse how the availability of excess heat can be estimated for an industrial process and how this industrial excess heat can be used, with a particular focus on electricity production and DH delivery. In addition to this analysis, understanding the effects of the recovery and utilisation of IEH is important from an energy systems perspective. To that end, this thesis closely analyses six case studies of kraft pulp mills and integrated pulp and paper mills in Sweden, looking particularly at the electricity production in organic Rankine cycles (ORC) and DH delivery possibilities when utilising excess heat. Generalisation aspects are covered by estimating the electricity generation potential from low and medium temperature industrial excess heat across the whole of the Swedish kraft pulp industry, and by comparing the application of ORCs for excess heat utilisation with other use cases from an energy systems perspective.

To achieve the aim of the thesis, the following research questions are answered:

1. How can the electricity generation potential using excess heat from an industrial process be estimated?
2. What is the availability of industrial excess heat and the electricity generation potential of using industrial excess heat in the Swedish kraft pulp and paper industry?

3. What are the effects of recovering industrial excess heat on the energy system in terms of global CO₂ emissions and economic aspects?

These research questions are related to the papers included in this thesis as shown in the table below.

	RQ1	RQ2	RQ3
Paper 1	X		
Paper 2	X	X	
Paper 3			X

1.2 Research journey

This thesis is the result of work on two research projects. The research started in the project “Development and application of new methods for identifying efficient ways to use industrial excess heat”, a collaboration between Linköping University, Chalmers University of Technology, and Profu. The project was financed by the Swedish Energy Agency. This project was part of the Swedish contribution to Task 2 of the Industrial Energy-related Technologies and Systems (IETS) / Annex 15 – Excess Heat, from the International Energy Agency (IEA), which ended in December 2018. The work on this research project resulted in Paper 1 and Paper 2. In addition, the Swedish contribution to Task 2 of Annex 15 is included in that project’s final report [21], as well as in the national project’s final report. The second project was “Resource-efficient electricity production using ORC technology in district heating plants and wastewater treatment facilities”, primarily financed by Swedish Energy Agency and Energiforsk, the work for which resulted in Paper 3. The work is also presented in the project’s final report [22].

1.3 Overview of papers included and co-author statements

Paper 1: Availability of excess heat from the Swedish Kraft pulping industry.

This paper evaluated the availability of industrial excess heat in the kraft pulping industry in Sweden by performing a heat integration analysis based on pinch analysis and optimisation on six case studies. These include process data for four real mills in Sweden, and simulated process data for two mills from the FRAM (Future Resource Adapted Pulp Mill) project, which were developed to represent typical kraft mills in Sweden. The concept of excess heat temperature signatures (XHT signatures) was introduced. Based on the results from the heat integration studies, an estimation of industrial excess heat availability from all kraft mills in Sweden was performed by means of a regression analysis.

Conceptualisation, research design, methodology and investigation were carried out by Matteo Morandin and Elin Svensson. The author of this thesis contributed with the heat integration and regression analysis and was responsible for the visualisations presented. Elin Svensson had the main responsibility for the manuscript. Simon Harvey supervised the work.

Paper 2: Electricity generation from low and medium temperature industrial excess heat in the kraft pulp and paper industry

This paper presented the potential for electricity generation from low and medium temperature industrial excess heat available within the kraft pulp and paper industry in Sweden. The work originated from the heat integration analysis and regression analysis performed in Paper 1 to evaluate the availability of industrial excess heat at kraft mills, but extended the scope by analysing the integration of electricity generation from excess heat in the range of 60–140°C, with the use of organic Rankine cycles (ORC). A modified excess heat temperature signature was applied, and an updated regression analysis estimated the availability of excess heat and the potential for electricity generation for all kraft mills in Sweden. This modification in the excess heat temperature signature aimed to provide heat signatures based on better thermodynamic considerations.

The author of this thesis is the main author of this paper and responsible for the conceptualisation, research design, methodology, investigation, and visualisation together with Elin Svensson, who also contributed extensively with the heat integration analysis. Magnus Wallén and Simon Harvey supervised the work and contributed with comments throughout the work and by reviewing the manuscript.

Paper 3: Assessment of the potential for small-scale CHP production using organic Rankine cycle (ORC) systems in different geographical contexts: GHG emissions impact and economic feasibility.

This paper analysed the potential for the application of small-scale ORC systems for electricity and heat production in different energy-system contexts. District heating plants in Sweden, the agroindustry in Brazil and industries with a demand for process heat in the UK were analysed. To provide a use case that could be directly compared among these three energy markets, one scenario involving IEH utilisation in all three countries was also presented. An economic and GHG emissions analysis was carried out and different scenarios for the future energy systems were considered.

The author of this thesis is the main author of this paper and had the main responsibility for the conceptualisation, research design, methodology, investigation and visualisation. Maria Johansson contributed to the writing of the manuscript and participated in all phases of the analysis, and supervised the work. Joakim Wren contributed to the estimation of electricity generation efficiencies and other aspects of the ORC equipment considered in the study.

2

Theoretical background

This chapter presents important concepts and definitions regarding industrial excess heat as defined in the literature. An overview of methods used in previous excess heat studies, as well as their characteristics, is presented. The final section presents a short review of technologies for industrial excess heat recovery.

2.1 Concepts and definitions of industrial excess heat

The definition of IEH varies in different sources. The report from IEA – Annex XV: Industrial Excess Heat Recovery – Technologies and Applications proposed the following definition [23]:

Excess heat is the heat content of all streams (gas, water, air, etc.) which are discharged from an industrial process at a given moment. A part of that can be internally or externally usable heat, technically and economically. If heat from a process is used externally and cannot be used internally as an alternative, it can be called white excess heat. If it is of biomass origin, it can be called green excess heat (a mixture is also possible). If the heat could have been used internally instead, technically and economically, it can be called black excess heat. Non-usable excess heat is the remaining part of the excess heat, when the internally and externally usable parts have been deducted. This part can be called waste heat. The often used term true excess heat can be defined as white or green excess heat, depending on fossil or biomass origin.

As a by-product of the industrial process, excess heat is usually a resource with lower exergy than the other energy carriers utilised during the production process. Thus, it is unavailable for utilisation within the same process. Because thermal processes never achieve 100% efficiency, and it is impossible to recover all the energy input to a system as useful work, a proportion of the energy is emitted as heat. The theoretical efficiency limit of a thermal process is defined by the Carnot efficiency, which is given by Eq. (1).

$$\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h} \quad (1)$$

where T_c and T_h are the temperatures of the heat sink and the heat source, respectively. Thus, the efficiency of a thermal process operating between two temperatures is increased if the temperature difference between heat sink and heat source increases.

Excess heat availability and utilisation potentials can be estimated in different ways, and when discussing excess heat potentials, it is important to make a distinction depending on which potential a particular method is based. Normally, these potentials are divided into three levels: the theoretical potential, the technical or technological potential and the economically feasible potential [20], as described in Figure 1.

Figure 1. Levels of potential. Based on source: [20].

The theoretical potential, therefore, is the potential that could be realised if the Carnot efficiency limit could be achieved in practice. However, this is not possible due to the various irreversible processes that occur in actual equipment. The technical potential is the potential achievable by current or proposed technology. However, not all of the technical potential can be realised in a profitable way, either because equipment has an efficiency that is too low, or because even if this efficiency is close to the technical limits, it is not profitable enough to justify its adoption.

2.2 Estimations of excess heat availability

Methods used to estimate available excess heat can be classified as top-down or bottom-up. Top-down methods start with the primary energy use and then, based on assumptions about conversion efficiencies and the allocation of the energy use to different processes, an estimation of the excess heat potential can be made for large process sites, whole industrial sectors or regions (group of municipalities, countries, etc.) [20]. The weakness of this method is that, while it is possible to achieve very good coverage of sectors or regions, it is generally not possible to estimate the temperature levels of the excess heat, or this estimation is superficial.

These methods have been used extensively to estimate the availability of excess heat in different countries and sectors. For example, McKenna and Norman [24] obtained a spatial distribution of heat loads and recovery potentials at different temperature levels, covering 60% of industrial energy use and 90% of energy use in energy-intensive industrial sectors in the UK. Data from the EU Emissions Trading Scheme (ETS) was used, together with sector-specific conversion factors, and an estimation for the technical recovery potential of excess heat amounting to 36–71 PJ was obtained, out of a heat demand of 650 PJ for industry. Based on this study, Hammond and Norman [25] analysed the application of different technologies for heat recovery in the UK, and concluded that on-site heat recovery and electricity generation show the best potential.

Similar estimations based on primary energy use and GHG emissions data are also available for, among others, Spain [26], France [27], the USA [28], Switzerland [29] and Germany [30]. Also based on [24], Papapetrou et al. [31] attempted to estimate the technically available IEH for the EU-28 by adapting the methodology to consider country-specific energy intensities and the distribution of industrial sectors. They found that the technically recoverable IEH is about 300TWh/year, one third of which is below 200°C. Persson et al. [32] also looked at the EU as a whole, focusing on excess heat recovery for DH, and found that 46% of the available heat could be recovered in regions with high heat demand densities. An attempt to derive global excess heat availability was made by Forman et al. [11], including not only the industrial sector but also the commercial, transportation, residential and electricity sectors. They concluded that industry generated just under 32000 PJ of excess heat in 2012, 42% of which was present below 100°C.

Bottom-up methods make use of data at a process level to build up the excess heat availability from individual sources, and sometimes aggregates the data to whole sectors or regions. Data for representative industries is collected. If the methods used to collect the data are detailed enough, more thorough conclusions such as the technical potential can be achieved [23]. Bottom-up estimations range from looking at one specific industrial site, such as a petrochemical cluster [33], an oil refinery [34,35], a pulp and paper plant [36] or a cement plant [37,38], to some sectors and municipalities [14,39], or to whole countries [40].

These bottom-up methods may collect data through questionnaires, direct process stream measurements, or public databases. Questionnaires are a suitable method for bottom-up studies that aim to aggregate data for whole regions or sectors, and have been used extensively [13,41–44]. However, due to the lack of a common definition of industrial excess heat, large variations in industrial sectors among regions and countries, and the different scopes of the studies, it is generally difficult to directly compare the results of such studies and to assess the precision of the results [20]. Direct process measurements are usually available in studies of process integration options for a particular industrial process. While there is an advantage in terms of detail for the energy flows analysed, such studies are generally only conducted for one or a few case studies.

2.3 Temperature intervals in excess heat studies

The most commonly used technologies to recover excess heat are heat exchangers in process streams, heat pumps, heat export to DH networks or direct export to another company or site, for example a biogas production plant [45]. There are also examples of low-temperature applications, such as greenhouse heating for farming or aquaculture [46,47]. The excess heat can also be converted into electricity, but because the excess heat temperatures or quantities are often too low to be used in conventional steam cycles, new technologies are emerging. Examples of such technologies are organic Rankine cycles (ORC), Supercritical CO₂ cycles and Kalina cycles. The recovery of excess heat also depends on the heat carrier phase (solid, liquid or gaseous streams), and the presence of contaminants or pollutants. Regardless of the technology employed, these uses can be divided up as follows:

- Direct use without upgrading

- Use after upgrading, through heat pumping
- Power generation

In most studies reporting IEH availability and potentials, the results are presented in an aggregated form in temperature intervals. The temperature intervals chosen for this vary broadly between studies. In addition, there is not always a differentiation between the carrier mediums in which the excess heat is found. The reasons for reporting the availability of IEH in this form varies. Studies based on top-down methods estimate the process conditions and adopt conversion efficiencies that are generalised for entire industrial sectors, based on primary energy uses and company size factors. On the other hand, studies based on bottom-up methods which do not directly measure the process stream, for example using questionnaires, might also lack the detail to understand the excess heat availability at a given temperature. One more factor of relevance is that the studies focus on different industrial sectors or different regions or countries, and these naturally involve industries with very diverse production processes at many temperature levels. For example, studies focusing on the iron and steel industry or the cement industry usually report much higher temperature levels of excess heat than studies in the pulp and paper industry or the food industry [31].

As a result, these different studies label the temperature levels as “low”, “medium” or “high”, sometimes with various complementary levels, in very different ways. As there is no uniform definition for IEH temperature levels, studies tend to use the levels suitable for their industry-specific cases. In countries with a cold climate, such as Sweden, much lower temperatures of excess heat than those usually considered are of interest, because there are potential applications at these lower temperatures that are interesting in these regions. Furthermore, some of the new technologies under development make it possible to recover excess heat at lower temperatures than established technologies, so that a more detailed division of temperature intervals below 250°C becomes necessary in these cases. Table 1 provides a compilation of the division of temperature intervals used in previous studies on industrial excess heat. The results presented are a non-exhaustive list of only the studies classifying the temperature intervals as low, medium and high. Several other studies use other definitions without characterising the intervals using such nomenclatures.

Table 1. Classification of IEH temperature intervals in different studies.

Source	Low	Medium	High
Brüeckner et al. [20]	< 100°C	100–400°C	> 400°C
Hirzel et al. [48]	< 150°C	150–500°C	> 500°C
DECC [49]	< 250°C	250–500°C	> 500°C
Johnson et al. [50]	< 230°C	230–650°C	> 650°C
Ma et al. [51]	< 150°C	150–500°C	> 500°C
Frederiksen and Werner [52]	< 100°C	100–400°C	> 400°C
Svensson et al. [53]	40–60°C	100°C	
Johansson and Söderström [54]	< 230°C		
Papapetrou et al. [31]	< 200°C	200–500°C	> 500°C
Forman et al. [11]	< 100°C	100–299°C	> 300°C
Jibrán et al. [29]	< 120°C	120–380°C	> 380°C

In this thesis, considering the specifics of the climate in Sweden and suitable heat recovery technologies, the temperature intervals and nomenclature presented in Table 2 are

proposed. The definition of more temperature intervals at lower temperature ranges is advantageous when seeking to identify excess heat recovery opportunities that can work at these lower temperatures. For the case of cold climates, such as that of Sweden, these can range from direct heat utilisation e.g. for comfort heating, heat upgrading in heat pumps or electricity generation technologies that work at lower temperatures. The introduction of fourth-generation DH networks (4DH), which work with network supply temperatures as low as 45–55°C [55], is also an important use case that is likely to gain relevance in the future.

Table 2. Temperature intervals and nomenclature considered in this thesis.

Excess heat category	Temperature range
Very high temperature	> 250°C
High temperature	≥ 140°C–250°C
Medium temperature	≥ 100°C–140°C
Low temperature	≥ 60°C–100°C
Very low temperature	≥ 40°C–60°C
Extremely low temperature	≥ 25°C–40°C

2.4 Technologies for the conversion of industrial excess heat into electricity

Rankine cycles convert heat into mechanical energy that is usually then converted into electricity. Rankine cycles with water as the working medium are the most widely used thermodynamic cycle in traditional electricity generation plants. However, the cycle running on water typically only achieves feasible efficiencies for heat sources above 240°C [56], and often above 300°C [57]. Lower temperatures and the corresponding lower steam pressures require larger equipment, and the heat available at such temperatures is not sufficient for superheating the steam to an acceptable level [14,58].

The temperature requirement of Rankine cycles running on steam, as well as other reasons, such as small-scale applications, has led to the development of other thermal cycles, but not only for excess heat recovery. These thermal cycles include Rankine cycles running on working fluids with lower boiling points, such as the organic Rankine cycle [59,60] and the Kalina cycle, or trans-critical and supercritical CO₂ cycles [57]. Researchers have also studied applications of technologies such as thermoelectric generators (TEG), phase change materials (PCM) and thermophotovoltaic generators (TPV).

2.4.1 Organic Rankine cycle (ORC)

Intense research has been carried out on ORC systems over the last decade, including for IEH applications (see e.g. [34,61–64]). ORC systems take advantage of organic working fluids that have lower boiling points than water, thus allowing the use of heat sources at lower temperatures with higher efficiencies than if water is used [63]. The choice of organic fluid is application-specific, and the options cover a wide range of boiling points. The fluid is usually selected to maximise efficiency, based on the temperature of the heat source [54], thermal stability and boiling point, but also taking into account environmental parameters such as global warming potential, ozone depletion potential and toxicity [65,66]. Tchanche

et al. [65] analysed 31 organic fluids for applications below 90°C in small-scale solar applications, while Saleh et al. [67] studied different cycle configurations applied to 30 organic fluids in geothermal applications below 120°C. As with other conversion technologies, the conversion efficiency depends on the difference in temperature between the heat source and the heat sink, but also on the thermodynamic properties of the working fluid, such as the enthalpy of vaporisation specific volume, critical temperature and pressure, as well as the composition in the case of mixed fluids [61,62,67].

One useful property of some organic fluids is that they have a positive or isentropic vapour saturation curve, whereas water has a negative saturation curve (called a “wet fluid”). Wet fluids can lead to fluid condensation at the end of the expansion process, which results in the need for fluid superheating to prevent damage to the turbine. Fluids with a positive vapour saturation curve are called “dry” fluids and remain as a vapour after expansion. The existence of a superheated working fluid after the expander also allows the inclusion of a recuperator after the expander, if the temperature of the superheated fluids after expansion is high enough to preheat the fluid before the evaporator.

2.4.2 Kalina Cycles

The Kalina cycle is also a Rankine cycle, but uses a binary medium composed of a variable mixture of ammonia and water. The proportion of ammonia and water determines the temperature range within which the fluid boils, with the boiling points optimised for each specific use. The use of a mixture of liquids with different boiling points increases the temperature range within which the cycle recovers heat from the heat source, thus theoretically yielding higher thermodynamic efficiencies than traditional cycles [68]. It is most suitable for medium to low temperature (80–180°C) heat sources, including gaseous and liquid streams. At these lower temperatures, the Kalina cycle is always more thermodynamically efficient than traditional Rankine cycles. Plants operating with the Kalina cycle are commercially available. However, this technology has not yet been tested to the same extent as ORCs [14].

2.4.3 Stirling engines

The Stirling engine is a closed thermodynamic cycle in which the working fluid is in a constant gaseous state. Unlike internal combustion engines, Stirling engines have the heat source located outside of the cycle, making them external combustion engines [69]. The engine provides a constant temperature for the heating and cooling process of the cycle during compression and expansion [69], making it suitable for applications where a constant temperature heat source can be supplied to the engine. The working medium is constantly being compressed and expanded due to the alternating heating and cooling of the gases. It is possible to use a Stirling engine for combined heat and power production (CHP), by transferring the heat from the process to water, for example to supply DH [70]. Stirling engines for use in CHP plants are commercially available, but other Stirling engines are under development to allow the recovery of heat from higher-temperature exhaust gases [13,71].

2.4.4 Phase Change Materials (PCMs)

Phase change materials (PCMs) have been widely researched for applications in heat storage solutions. The principle of the working of the PCM engine is the volumetric

expansion of a PCM when there is a phase change from liquid to solid. The aim of the engine is to generate electricity. For this application, a paraffin mixture is used, and the composition is adjusted to create better efficiencies at the required operating temperatures. The main component of the engine is an energy cell, which converts heat into mechanical energy. A heat source heats up the paraffin, which is melted to the liquid state and expands under high pressure. The cycle continues with the paraffin being cooled down by a heat sink, usually water, and returning to the solid state, completing one cycle. During the expansion and contraction processes, a hydraulic system converts the movement of the energy cell into mechanical energy. The mechanical energy is then converted into electricity in a generator. The PCM engine is currently the technology that is capable of converting excess heat into electricity at the lowest temperatures, working from 25°C upwards [72,73]. The technology has seen commercial introduction, but active development has stopped and the company commercialising the technology went out of business.

2.4.5 Thermoelectric generator (TEG)

Thermoelectric generators take advantage of the Seebeck effect. This is the occurrence of a differential electrical potential in a semiconductor or conductor material caused by a temperature gradient through the material [72,74]. The magnitude of the induced voltage in relation to the temperature gradient is called the Seebeck coefficient. The most common material used is bismuth telluride (Bi_2Te_3), but quantum-well thermoelectric materials, such as silicon–germanium (SiGe), are also used [75]. The voltage difference caused by the temperature gradient results in a flow of electric charges, and when the circuit is closed, the result is an electrical current. The generator is constructed by linking thermocouples of materials with different Seebeck effect coefficients, and these thermocouples are arranged electrically in series and thermally in parallel. The number of thermocouples connected in series determines the output voltage of the generator, but this output is also dependent on the Seebeck coefficients of the semiconductors and the temperature difference between the heat sinks and heat sources. Each thermocouple has an optimal performance within a specific temperature range, and a TEG can include different materials in segments optimised for the various temperature ranges [75].

The thermoelectric materials that are commercially available are divided into three groups [72]:

- low-temperature materials, up to about 250°C (e.g. materials based on bismuth telluride);
- intermediate-temperature materials, up to about 600°C (e.g. materials based on lead telluride);
- high-temperature materials, up to about 1000°C (e.g. silicon germanium alloys).

The conversion efficiency depends on the temperature difference between the hot and cold sides of the generator, and is highly dependent on the temperature of the heat source.

2.4.6 Thermophotovoltaic generator (TPV)

The thermophotovoltaic generator produces electricity directly from infrared radiation emitted from a high-temperature heat source, in a similar way to conventional photovoltaic

(PV) cells powered by solar radiation. The thermophotovoltaic cell is made up of diodes, in which the semiconductors are doped with different materials, creating valence bands that can be excited by photons. The movement of electrons from a valence band to a conduction band produces an electric current. Comparing the TPV with a conventional PV cell, the former have smaller band gaps that are optimised to absorb photons in the infrared radiation spectrum, resulting in higher efficiencies. The efficiency of the system depends on the match between the spectrum of the radiation of the heat source and the optimum photon energy for the specific diode [76,77].

2.4.7 Comparison of the excess heat conversion technologies

Table 3 presents a comparison of the excess heat recovery technologies presented in this section, including other technologies for reference.

Table 3. Technologies for conversion of industrial excess heat. Compiled with information from: [13,41,54,58,78,79].

Technology	Working temperature (°C)	Heat source phase	Unit size (kW _{el})	Electrical efficiency (%)	Stage of development
Rankine cycle	>240	Gas, steam	0.5–1 500 MW	⁴⁷ Condensing 30 CHP	Commercial
ORC	30–550	Gas, liquid	5 kW–15 MW	5–20	Commercial
Absorption Rankine cycle	70–170	Gas, liquid	80–130	15	Demonstration
PCM	25–95	Liquid	10–1000	2.5–9	Experimental development
Kalina cycle	80–180	Gas, liquid	0.05–12 MW	12–17	Commercial
CO ₂ trans-critical	60–540	Gas, liquid	0.25–8 000	2.5–15	Experimental development
TEG	150–800	Gas, liquid	200–800	1.5–5	Small-scale commercial
TPV	1 000–1 800	Gas, liquid	-	1–2	Experimental development
Stirling cycle	100–700	Gas, liquid	100–300	13–36	Demonstration, commercial

3

Cases studied

This chapter presents the cases studied in this thesis. An overall description of the pulp and paper industry in Sweden is presented, with particular focus on the kraft pulp and paper sector. This sector is the focus of analysis in this thesis. Thermal stream data obtained from past studies of kraft mills in Sweden were utilised as the basis for the study presented here. These are four kraft mills in operation, plus two simulated mills that resulted from a research project attempting to characterise typical Swedish kraft mills. Further details of each of these mills are presented in Chapter 0. To further address systems aspects of excess heat recovery under different energy market conditions, three countries were studied to highlight how the electricity and heat market in which an industrial process is inserted affects the feasibility of different IEH recovery options regarding profitability and GHG emissions. These countries are Sweden, the United Kingdom and Brazil.

3.1 The pulp and paper industry in Sweden

The pulp and paper industry (including all the types of pulp production) is the largest energy user in the Swedish industrial sector. In 2017, this sector accounted for 50.5% of the final energy use in the industrial sector in Sweden (72.4 TWh out of 143.2 TWh) [80]. There are different types of mills in operation, but 61% of the total pulp production in 2017 in Swedish mills came from kraft mills [81], and Swedish mills accounted for around 31% of European pulp production in 2018 [82]. These mills convert large amounts of biomass feedstock. In the kraft process, a significant fraction of the lignin and hemicellulose content of the incoming biomass raw material leaves the mill digester in the black liquor stream, which is evaporated and burnt for chemical and energy recovery. The energy recovery results in process steam and electricity production that partially supplies the electricity requirements of the mill operations. The renewable electricity certificates system that was introduced in Sweden in 2003 has contributed to a substantial increase in the production of electricity in pulp and paper mills, since the process runs on biomass [83]. Figure 2 shows the trends in heat and electricity sales in the kraft pulp industry over the past 18 years. While the amount of kraft pulp production has varied by about 18%, heat sales varied by up to 65% and electricity sales by more than eight times. In terms of specific values per kilotonne of pulp produced, heat and electricity sales show a general upward trend. While this might indicate increasing energy efficiency over the years, other factors must also be considered, e.g. the amount of biofuel used by the mills solely for heat and electricity production.

Figure 2. Total kraft pulp production, heat and electricity sales, together with specific heat and electricity sales per kilotonne of pulp produced for the years 2002 to 2020. Compiled with data from [81].

Figure 3 shows the declared amount of electricity produced in pulp and paper mills in Sweden in 2019 in relation to biofuel used (including black liquor, bark and other wood residues). For the case of kraft mills, there is a clear linear relationship between biofuel usage and electricity production.

It is also common in Sweden for pulp and paper mills to export a certain amount of heat to nearby district heating systems (see Figure 3). However, in this case, the relationship between the amount of heat exported and biofuel usage is less clear.

Figure 3. Left: declared electricity production vs. biofuel use in Swedish mills in 2019. Right: declared excess heat sold vs. biofuel use in Swedish mills in 2019. Compiled with data from [81].

3.2 Countries and system configurations studied

As part of the evaluation of IEH recovery options, a comparison of the IEH recovery options and alternative heat and electricity production (cogeneration) in small-scale CHP plants is proposed. Additionally, in order to take into account the different geographical contexts and settings of IEH recovery and small-scale CHP production, three countries with different climates, energy markets and regulations in the electricity sector were selected: Sweden, the UK and Brazil. Sweden and the UK have low annual average temperatures, and thus a demand for comfort heating exists. In Brazil there is almost no demand for comfort heating. While a demand for heating exists in Sweden and the UK, the way in which this demand is met is different. Sweden has a prevalence of district heating (DH) systems [80], while in the UK only 2% of the heat demand is met by DH networks [84], and individual heating units are common. The ORC systems analysed are installations in: 1) a Swedish district heating system using biomass boilers (SE1), 2) a sector of the manufacturing industry in the UK (UK1), and 3) a sector of Brazilian agroindustry (BR1). Additionally to these three cases, IEH recovery for electricity generation based on ORCs was also included in the analysis for the three countries (labelled SE2, UK2 and BR2, respectively). ORC systems between 50 and 2000 kW installed electrical power are considered. A general description of the local conditions that are relevant to the analysis is presented in this section for each of the countries considered. Table 4 summarises the taxes and network costs of the three countries analysed.

Table 4. Electricity network costs and taxes and fees used for the economic calculations. Exchange rates used are 1 GBP = 1.127 EUR, 1 SEK = 0.104 EUR, 1 BRL = 0.235 EUR. The prices shown are for customers using 2000–19 999 MWh annually for the UK and Sweden and for average industrial customers in the regulated market for Brazil.

Costs	Sweden	United Kingdom	Brazil
Network costs (EUR/MWh)	17.30 ^{1,2}	27.20 ^{2,3}	40.88 ⁴
Taxes and levies, excl. VAT (EUR/MWh)	3.90 ^{1,2}	49.70 ³	32.74 ⁴
VAT (%)	25	20	18 ⁵

¹ [85]

² [86]

³ [87]

⁴ [88]

⁵ In the state of São Paulo.

3.2.1 Sweden

All major Swedish cities have district heating systems [89], but only about 20% of these employ CHP production [90]. Often, the large systems involve CHP production, while the small systems mainly employ heat-only boilers (HOB). These small systems often have a capacity of 2–10 MW_{th} and are fuelled with wood chips, and so there is potential to install an ORC system running as CHP plant.

In case SE1, it was assumed that the ORC is installed in a small DH system and that the heat output from the system is maintained. Therefore, additional biomass is bought for the boiler to produce the extra heat needed for electricity production. ORC systems in this

application are designed to use the boiler as heat source and reject heat to the DH return flow. The temperature difference between the boiler and DH return is typically low, between 60–100°C, resulting in low electrical efficiency (2–10%). However, the marginal electricity efficiency is close to 100% because nearly all the heat supplied to the ORC system is either converted to electricity or used to heat the DH return. An assumption was made that for up to 1000 kW_{el} installed capacity, the electricity produced is for self-use by the DH plant to cover its own electricity requirements. This results in avoided costs for electricity purchase, grid costs and some tax exemptions. It is also assumed that 20% of production above 1000 kW_{el} is sold to the grid for plants larger than 1000 kW.

Sweden has renewable electricity certificates, which pay a premium for renewable electricity production [91]. Eligible production receives certificates for 15 years. There is a tax exemption for renewable electricity production up to 100 [92]. Regardless of the installed capacity, a tax reduction to 0.5 EUR/MWh is applied to the share of electricity used in-house.

3.2.2 The United Kingdom

The ORC is assumed to be installed by an industrial company with a demand for process heat in case UK1. The electricity is produced for self-use, with the implication that it avoids the costs of purchasing an equivalent amount from the grid. The company owns a biomass boiler, which is connected to the ORC system. To meet the company's heat demand, there will be an increased purchase of biomass to cover the electricity production. The most relevant policy related to renewable electricity in the UK is the Smart Export Guarantee (SEG). This requires electricity suppliers to purchase electricity surplus from renewable sources and applies to micro-CHP electricity generation up to 50 kW_{el} or electricity-only generation up to 5MW [93].

3.2.3 Brazil

The agroindustry is one of the most important sectors in Brazil and includes the production of livestock, coffee, soybeans, sugarcane and citrus [94]. Large amounts of biomass waste are generated and are largely used as fuel in the production of process heat. The amount of biomass waste is often greater than the demand for process heat, and the waste is sometimes burnt without energy recovery. The National Energy Plan 2030 [95] proposes greater adoption of biomass cogeneration in CHP plants, especially using sugar cane bagasse.

In case BR1, it is assumed that the ORC is installed at an agroindustry. It is also assumed that there is a biomass excess in the plant, in which case the fuel could be free, but a fuel cost is considered for this case as the case BR2 already excludes heat costs. The electricity produced is assumed to be used self-used, which results in avoided costs of purchasing electricity from the grid.

The electricity market in Brazil is partially regulated, depending on the power demands of the consumer. In general, consumers with a power demand below 500 kW are captive consumers, and can only contract with the local power distribution company. This regulated market encompasses 70% of the total power demand, and charges prices approved by the national electricity market regulatory agency [96]. From January 2021 onwards, the deregulated market has been accessible to users with a contracted demand above 1500 kW, who are free to trade electricity in the deregulated market [97]. Consumers with a demand

between 500 kW and 1500 kW can trade in the deregulated market only for electricity from certain renewable sources, which include solar, wind, biomass and small-scale hydropower. These renewable sources benefit from exemptions in transmission and distribution fees. There is also a simplified scheme for distributed generation from renewable sources up to 5 MW [98].

4 Methods

This section presents the series of steps taken for (1) assessing the availability of excess heat in an industrial process and corresponding (2) excess heat-temperature (XHT) signatures, (3) performing the regression analysis and validation of electricity generation and DH delivery potentials, and finally (4) obtaining the new electricity generation targets and performing the economic CO₂ emissions balances. An overview of the procedure is shown in Figure 4, and the procedure is explained below.

Figure 4. Overview of the methodology employed to obtain the availability of industrial excess heat and calculate the electricity generation potentials together with DH deliveries. The final step is the analysis of the IEH utilisation options, taking into consideration the energy-market scenarios.

Thermal stream data from six case studies (Thermal stream data from case studies) and key production data for the pulp and paper sector in Sweden reported in an open database (Sectorial public database) was used to calculate targets for conventional electricity generation, using backpressure and condensing steam turbines. After the integration of the targeted steam turbine cycles, the availability of excess heat was estimated for each of the case studies (XHT signatures (case studies)). Based on these case studies, a regression model was proposed to estimate the availability of excess heat for each of the kraft pulp and paper mills in Sweden. The regression model was validated against the results of the case studies. Based on the regression analysis, electricity generation potentials from low and medium temperature IEH for all Swedish kraft pulp and paper mills were obtained. All these steps were combined and executed in MATLAB, by using and modifying the pinch analysis and optimisation framework developed by Morandin et al. [99]. Following this

analysis, the original excess heat estimations for the six case studies were also analysed in more detail to present an economic and CO₂ emissions comparison of utilisation options for IEH, basically comparing the option of direct heat deliveries to DH networks and electricity generation using ORC technology. This analysis for economic and CO₂ emission trade-offs considered different energy-market conditions by using several future scenarios for the energy systems, providing a systems approach for the analysis. Each of the steps taken is presented in more detail in this section.

4.1 Availability of industrial excess heat and calculating electricity generation potentials

4.1.1 Thermal stream data from case studies and sectorial public database

Process data collected in previous studies of Swedish kraft pulp and paper mills was used to estimate the excess heat availability for four kraft mills [100–103]. Also, data from the FRAM (Future Resource Adapted Pulp Mill) project, which defined benchmarks for the processes in the pulp and paper industry, was obtained for a typical kraft bleached market pulp mill [104] and a typical kraft integrated (pulp and paper) mill [105].

Table 5 presents a summary of the data collected for the six case studies. Data for the market pulp and paper production, energy use, electricity production and heat deliveries was retrieved from Miljödatan for the period 2002 to 2020 [81]. Miljödatan is a resource that is available online and contains data provided by the Swedish Forest Industries Federation, reporting on key operational parameters for most of the pulp and paper mills in the country. Data from this database was selected for the same year in which the study that collected process stream data was carried out. For the original studies, see the references in Table 5. The studied mills may have undergone substantial revamping and retrofitting since the year when the data was collected. Data for SCA Östrand, in particular, is representative of a plant expansion planned in 2015, in which case the stream data was obtained from simulations, equipment quotations and the experience of process experts, and may therefore be subject to larger errors when compared to the case studies based on actual measurements.

Table 5. Overview of kraft mill study cases. Data taken from Miljödatan [81] and the respective studies, with the exception of the FRAM mills [106,107].

Mill	Södra Cell Värö	SCA Östrand	Holmen Iggesund	Billerud-Korsnäs Karlsborg	FRAM type pulp mill	FRAM type integrated mill
Pulp prod. (kt/y)	419	900 (+95)	347	272	327	385
Market pulp (kt/y)	419	900 (+95)	50	151	327	0
Paper/board (kt/y)	0	0	381	151	0	512
Biofuel (GWh/y)	3 035	n/a	2 327	1 952	1 975	2 594
Fossil fuel (GWh/y)	31	n/a	66	48	0	0
El. prod. (GWh/y)	358	n/a	303	224	259	270
Heat sold (GWh/y)	91	n/a	-	-	-	-
Data year	2012	2015	2013	2009	2006	2008
Data source	Mostly measurements	Quotations and models	Mostly measurements	Mostly measurements	FRAM models	FRAM models
Mill type	Market pulp	Market pulp	Integrated	Integrated	Market pulp	Integrated
Process thermal data reference	Bood and Nilsson [100]	Ahlström and Benzon [101]	Isaksson et al. [102]	Eriksson and Hermansson [103]	Axelsson et al. [106]	Axelsson and Berntsson [107]

4.1.2 Targeting conventional electricity production with steam Rankine cycles

In kraft pulp mills, black liquor is burned in a recovery boiler for the recovery of energy and the regeneration of cooking chemicals. The steam production is determined by the amount of black liquor being processed, which in turn depends on the production rate in the pulp digesters. The recovery boilers are therefore regarded as part of the production process and not a utility system. On the other hand, other steam boilers, which in pulp mills are mainly fuelled with bark, are regarded as part of the utility system and not as necessary parts of the process itself.

The high-pressure steam produced in the recovery boiler, and possible additional steam boilers (also called power boilers), is distributed around the process site through a steam utility network, which may also be equipped with steam turbines the combined production of heat and electricity. The fuel energy utilisation in this steam utility system will be maximised if the process steam demand is exactly covered by back-pressure steam from a turbine. In practice, there is usually a mismatch between steam production, the steam turbine cycle and process steam demand. Typically, there will either be an excess of steam, providing an opportunity for a condensing turbine stage, or a deficit of steam and therefore a need for direct reduction of boiler steam through let-down valves, thereby by-passing the steam turbine. In the latter case, it might be justified to increase the back-pressure electricity generation, by firing additional fuel in the utility boilers to produce more steam.

To estimate the electricity generation targets from conventional steam cycles and excess heat availability, an energy targeting methodology was employed, based on an investigation of heat flows between the constituent processes using pinch analysis tools. Pinch analysis is a widely used method to evaluate the energy requirements of an industrial process (energy targeting) and to develop heat exchanger networks [108]. The targeting procedure is formulated as a linear programming problem following the combined objective of maximum electricity generation and maximum excess heat recovery, given certain constraints representing the assumptions about the level of heat recovery and fuel use. In

principle, a steam cycle was integrated between the available high-temperature combustion heat from the recovery boiler and the heat demands of the production process [109]. Figure 5 shows a graphical representation of this integration between the steam cycle, the process and the recovery boiler, in a background/foreground analysis. This is equivalent to fitting the steam cycle between the different levels of heat available from the recovery boiler and the heat requirements of the process. In this background/foreground analysis, the grand composite curve (GCC) obtained from the pinch analysis is split into the streams of a foreground process of interest, and all other streams remain shown as a background process, allowing for a direct inspection of heat integration opportunities in the figure obtained (see Figure 5).

Figure 5. Integration of a steam turbine cycle with the pulp mill process using heat from the recovery boiler. Left: Heat availability from the recovery boiler shown as a background process, and heat demand from the pulp mill shown as a foreground process. Right: Back-pressure and condensing turbine operation shown as a foreground process and heat from the recovery boiler plus process heat pulp mill demand as a background process.

4.1.3 Excess heat-temperature (XHT) signatures for case studies

Based on the integration of the production process, steam boiler and turbine system, the availability of excess heat is then characterised according to discrete pre-defined temperature intervals, as presented in Section 2.3 (Table 2). These temperature intervals prioritise the recovery of excess heat at higher temperatures over lower temperature levels according to Carnot-based weight factors (see Table 6). The excess heat temperature profiles are calculated following the objective function shown in Eq. (2).

$$\text{minimize } f = \sum_{i=0}^{10} (WF_i \cdot x_i) \quad (2)$$

where WF_i is the normalised weight factor for temperature interval/level i , and x_i is the heat available within the same interval/level i (see Table 6).

The resulting temperature profile is referred to as the excess heat temperature (XHT) signature, as discussed in detail by Svensson et al. [110] and Svensson et al. [109].

Table 6. Categories of excess heat according to temperature levels, average Carnot factors and normalised weight factors for optimisation. $T_{amb} = 273.15\text{K}$ and T_{IEH} is the temperature of the excess heat.

Excess heat category	Temperature range	Heat enthalpy notation (x_i)	Average Carnot factor ($1-T_{Amb}/T_{IEH}$)	Normalised weight factor (WF)
Very high temperature	500°C–250°C	x_{10}	0.5623	-6.71
	250°C–250°C	x_9	0.4779	-5.70
High temperature	250°C–140°C	x_8	0.4084	-4.87
	140°C–140°C	x_7	0.3389	-4.04
Medium temperature	140°C–100°C	x_6	0.3034	-3.62
	100°C–100°C	x_5	0.2680	-3.20
Low temperature	100°C–60°C	x_4	0.2240	-2.67
	60°C–60°C	x_3	0.1801	-2.15
Very low temperature	60°C–40°C	x_2	0.1539	-1.84
	40°C–40°C	x_1	0.1277	-1.52
Extremely low temperature	40°C–25°C	x_0	0.0839	-1

The assumptions about the integrated steam cycles heavily affect the estimated availability of excess heat from the mills. Excess heat availability is estimated for two different sets of assumptions: one theoretical scenario representing minimised fuel use and one scenario representing the current utility demands of the process, here called the process cooling scenario. In accordance with these two sets of assumptions, two different XHT signatures are constructed: a theoretical XHT signature and a process cooling XHT signature.

The theoretical XHT signature represents the unavoidable excess heat corresponding to minimised fuel use [111]. This implies assumptions about the theoretical, maximum internal process heat energy recovery, assuming a minimum temperature difference of 0°C for all heat exchangers. This is represented by the process grand composite curve (GCC) with $\Delta T_{min} = 0^\circ\text{C}$. Furthermore, the steam cycle is sized to avoid additional firing of bark in the power boiler unless required to be able to cover the process heat demand, which means that when the energy content of the steam produced in the recovery boiler is insufficient to cover the process steam demand in combination with maximum back-pressure power generation in the steam turbine cycle, some steam will bypass the steam cycle and be directly reduced to lower pressure. State-of-the-art values are assumed for steam boiler outlet conditions, as well as turbine and pump efficiencies. A condensing turbine stage is considered if an excess of low-pressure steam is still available after minimised fuel use and maximised back-pressure electricity generation, but only if the extra power produced by the condensing stage is greater than 10 MW. This limit was set to avoid excessively small turbines that generally fail to meet industrial profitability criteria [112]. Note that the inclusion of a condensing turbine limits the amount of excess heat available as steam, and also reduces the amount of excess heat available from the pulp mill process

because heat is used for heating the condensate from the turbine condenser up to feedwater temperature.

The process cooling XHT signature represents the current availability of excess heat from existing process coolers and exhaust streams. In the absence of detailed data about air or water coolers in each mill, the process cooling XHT signature was also estimated using a targeting approach. In this scenario, heat exchange was assumed to be possible with a minimum temperature difference of 5°C, but layout and operability limitations were also considered. In particular, direct process-to-process heat exchange was assumed to be possible only between a few specified thermal streams, such as inlet cold air and outlet hot air in the air driers, while heat recovery between most of the process heat sources and heat sinks was assumed to be accomplished via secondary warm and hot water systems. This system was modelled as thermal loops between 20°C and 60°C, and between 20°C and 80°C, for warm and hot water respectively. For the process cooling XHT signature, the steam cycle was sized according to reported values of biofuel use in the mills [81]. This was achieved by estimating the amount of black liquor obtained from the pulp process in comparison with the declared amount of biofuel use reported by the companies. As discussed earlier, this difference was assumed to be available as bark. Steam values and turbine efficiencies were assumed to represent those of modern mills, but with more moderate values compared to the state-of-the-art assumptions used for theoretical XHT signature. The assumptions for the estimation of excess heat availability and conventional electricity generation targets are summarised in Table 7.

Table 7. Assumptions for the heat integration study. Note: The amount of bark used to obtain the Process cooling XHT is the difference between total biofuel input and the black liquor resulting from the pulp process.

	Theoretical XHT	Process cooling XHT
Black liquor useful energy	6.046 MWh/ADt pulp	6.046 MWh/ADt pulp
Bark	-	Total biofuel – black liquor
$\Delta T_{\min}$	0°C	5°C
High-pressure steam conditions	100 bar, 530°C	80 bar, 480°C
Turbine isentropic efficiencies	Back-pressure: 0.85 Condensing: 0.9	Back-pressure: 0.75 Condensing: 0.85
Condenser pressure	0.1 bar	0.1 bar
Additional steam production	-	16 bar
Secondary heating system	-	20–60°C and 20–80°C

As an example, Figure 6 shows a theoretical XHT signature, assuming that a steam cycle with an additional condensing stage is integrated with the process.

Figure 6. Estimated theoretical XHT signature for the Södra Värö pulp mill, based on the net cooling demand represented by the GCC of the integrated pulp mill process, recovery boiler and steam cycle.

4.1.4 Regression analysis – XHT signatures for all Swedish kraft mills

After analysing the excess heat availability and obtaining the conventional electricity generation targets for the six case study mills, a linear regression function was postulated to estimate the excess heat availability of each kraft mill in Sweden. In order to obtain as significant a regression as possible, different data available from the online database mentioned previously was tested, and the market pulp (not the total pulp produced) and paper production rates were selected as most significant for the regression. The linear regression analysis was conducted using Eq. (3) for each of the 11 temperature levels that were used to represent the XHT signatures (see Table 6), provided that excess heat availability was estimated at those levels. Constant mill production was assumed, for a mill availability of 92% (7834 hours/year), reflecting the process conditions when thermal stream data was collected [104].

$$\text{Excess heat (GWh/y)} = k + m \cdot \text{Market Pulp (kADt/y)} + n \cdot \text{Paper (kADt/y)} \quad (3)$$

The regression functions obtained were then used to calculate the theoretical and process cooling XHT temperatures of each kraft mill in Sweden and were later used to estimate the electricity generation potentials from low and medium temperature excess heat available at these mills.

4.1.5 Estimation of new electricity generation potentials from low and medium temperature excess heat using organic Rankine cycles

The estimation of electricity generation potentials from low and medium temperature IEH in the kraft mills considered evaporator temperatures following the XHT signatures obtained, and cooling water was assumed to be available at 15°C. This temperature is consistent with cooling water temperatures available in Sweden even during the summer months, and the estimation of the cycle net efficiency gives a minimum value of the efficiency achievable, whereas during the winter months the efficiencies would be slightly

higher. The two ORC cycles considered in the analysis of different energy markets (Section 3.2) consider evaporator temperatures of 120°C and condenser temperatures of 60°C for the small-scale CHP delivering DH, or 25°C for the ORC cycle producing electricity from IEH.

Dickes et al. [113] developed a Matlab-based simulation tool for ORC cycles, ORCmKit. Among a series of options, there is a model for an ORC cycle with an internal heat exchanger (recuperator). Ziviani et al. [114] further developed this simulation tool to include a charge-sensitive analysis of ORC cycles. The tool includes semi-empirical ORC cycle models for the cycle components, calibrated with experimental data. This tool was used and adapted to estimate the ORC cycle characteristics, including the net efficiency of the ORC at the IEH temperature levels considered. Figure 7 presents the T-s diagram of an example ORC cycle using the Matlab tool for IEH recovery at 100°C, and cooling water temperature at 15°C. The heat profiles of the IEH source and cooling water are shown, together with the cycle component points for a cycle running on R245fa (see Table 8 for fluid characteristics). R245fa is a common refrigerant for ORC cycles working at the temperature levels analysed in this thesis.

Figure 7. ORC cycle simulation using the ORCmKit simulation tool [113], adapted to the operating conditions for IEH recovery at 100°C, as an example.

Table 8. Selected working fluid for ORC application.

Working fluid	T critical (°C)	P critical (MPa)	Boiling point (°C)
R245fa	153.9	3.651	15.3

The net efficiencies of the ORC systems were calculated on ORCmKit [113] based on the cooling water temperature and other system parameters mentioned previously. Additionally, a subcooling of 2°C at the condenser exit and minimum temperature difference in heat exchangers from Table 7 were considered. The net efficiency of the cycle ($\eta_{\text{net,ORC}}$) was obtained according to Eq.(4).

$$\eta_{\text{net,ORC}} = \frac{\dot{W}_{\text{el,net}}}{\dot{Q}_{\text{ev}}} = \frac{\dot{W}_{\text{exp}} - \dot{W}_{\text{pp}}}{\dot{Q}_{\text{ev}}} \quad (4)$$

where $\dot{W}_{\text{exp}}$ and $-\dot{W}_{\text{pp}}$ are the expander power generation and pump power use, respectively, and $\dot{Q}_{\text{ev}}$ is the evaporator heat transfer rate. In case of an ORC unit running as a CHP plant, the ratio of electricity production to heat delivered (alpha-value) is obtained using Eq. (5), and the marginal electric efficiency using Eq. (6) [115].

$$\alpha = \frac{\dot{W}_{\text{el,net}}}{\dot{Q}_{\text{cd}}} \quad (5)$$

where $\dot{Q}_{\text{cond}}$ is the heat transfer rate delivered by the condenser.

$$\eta_{\text{el,marginal}} = \frac{\dot{W}_{\text{el,net}}}{\dot{Q}_{\text{extra}}} = \frac{\alpha}{(1+\alpha)/\eta_{\text{tot}} - 1/\eta_{\text{alt}}} \quad (6)$$

with $\dot{Q}_{\text{extra}}$ defined as the extra heat transfer rate need by the ORC to supply the same amount of heat as an alternative heat production, η_{tot} is the total efficiency and η_{alt} is the efficiency of the alternative heat production. A biomass boiler with an efficiency of 90% was considered as the alternative source of heat production. With the α value obtained from the cycle simulations, it is possible to easily obtain the extra heat ($\dot{Q}_{\text{extra}}$) needed for the ORC to replace an alternative heat production unit.

The ORC net efficiencies obtained are shown in Figure 8. These efficiencies are equivalent to the technical potential of IEH utilisation, as discussed in Section 2.1. In Figure 8, condenser temperatures from 5°C to 15°C are shown for the IEH recovery options in kraft mills. For the comparison of IEH recovery and CHP cogeneration, condenser temperatures of 25°C and 60°C are shown, respectively.

Figure 8. ORC net efficiencies obtained for IEH recovery and CHP cogeneration options.

The XHT signatures used for identifying excess heat amounts for low and medium temperature electricity generation are obtained either through the optimisation targeting approach described in Section 4.1.3, for the case study mills, or through the regression analysis described in Section 4.1.4 (for all Swedish kraft mills). The XHT signatures represent potential excess heat utilisation integrated with a process, considering a specified minimum temperature difference for heat recovery. Therefore, estimated amounts of heat available for electricity generation technologies working at different temperature levels can be read directly from an XHT signature curve. As an example, the XHT signature obtained through regression analysis representing the process cooling availability of excess heat for Södra Våro is shown in Figure 9, and illustrates how the heat available for low-temperature electricity generation is read from the curve. The cycle's actual electricity generation is then calculated based on the estimated amount of heat available and the net efficiencies at each temperature level.

4.1.6 Estimation of DH delivery potentials

The average supply temperature of DH networks in Sweden is 86°C, whereas the average return temperature is 46°C [116]. These were chosen as the supply and return temperatures to evaluate the potential of utilising excess heat for direct heat deliveries. In reality, the supply and return temperatures vary for each network, and are also dependent on seasonal temperature changes. The evaluation of the potential for direct heat deliveries was carried out in the same way as the estimation of the excess heat recovered by the ORC equipment, with the difference that, instead of a fixed temperature level, the supply and return temperatures of 86°C and 46°C are considered (see Figure 10).

Figure 9. Estimation of excess heat recovered by the ORC at each temperature level. The XHT signature (red line) represents the potential IEH recovery integrated with the process, and at each temperature level the ORC system evaporator temperature is selected to recover the available heat.

Figure 10. Example of estimation of IEH recovery to DH deliveries.

4.2 Scenarios and CO₂ emissions balance

The CO₂ emissions balance and analysis, like the economic analysis, is based on a systems perspective [117]. This requires a holistic approach, with the system analysed being expanded to include the effect of the excess heat utilisation option. The utilisation options considered for IEH result in either electricity generation or direct heat deliveries externally to the source site. This results in two situations that must be considered separately. When

system expansion is considered, in the case of electricity generation onsite, this electricity will have an impact on the overall energy system by reducing the electricity production of other producers in that energy market, thus displacing the build margin electricity production in the energy market. In this case, the CO₂ emissions due to the electricity generation onsite and those due to the marginal electricity generation in the system need to be compared. Pulp and paper mills in Sweden process large amounts of biofuel, and fossil fuel use is relatively small compared to the total energy use of the mills (see Table 5). For this reason, it is assumed that no excess heat arises from fossil fuels, and no allocation of CO₂ emissions is made for the utilisation of IEH.

The second case of excess heat utilisation is the export of heat to a DH network, and in this case, the heat delivery will replace DH production that would otherwise be needed for the DH network. In this study, two cases are considered for the alternative heat production that IEH is replacing. In the first case, a Bio-CHP is displaced by the delivery of IEH. Because Bio-CHPs run on biofuel, their CO₂ emissions are very low, but the substitution by IEH will also result in no electricity being produced from that unit. In this case, there are two aspects to consider: the lost electricity production needs to be replaced by other electricity capacity in the system, and biomass from the Bio-CHP plant is made available for use elsewhere in the system. If biomass is considered a limited resource, it could replace fossil fuel demand elsewhere, with very advantageous climate benefits in terms of CO₂ emissions. This is further discussed in Section 4.2.1. In the second case, a bio-HOB is considered, and no electricity production is lost by replacing the heat delivery with IEH. As in the first case, biomass that would be used for heat production is made available for use elsewhere, and if biomass is considered a limited resource, this creates CO₂ emissions benefits. Figure 11 shows a schematic representation of the system boundaries, the systems studied and the interactions between the different IEH utilisation options considered in the study and the surrounding energy system.

Figure 11. System boundaries, system studied and interaction with the expanded surrounding energy system. Dashed stream lines represent alternative streams which depend on the IEH utilisation options considered.

4.2.1 Energy-market scenarios

In order to take into consideration the evolution of energy prices and specific CO₂ emissions from electricity generation under future conditions, energy-market scenarios based on the ENPAC (Energy Price and Carbon Balance Scenarios) tool were used. This tool was originally developed to provide support in the evaluation of energy prices and CO₂ balances for investments in industrial energy projects [118]. ENPAC provides consistent scenarios for fuel and energy prices, as well as the inherent CO₂ emissions of expected future build margin electricity generation technologies. The calculations are for large-scale users of energy and fuels in the European context, and take into consideration future fossil fuel prices, the effect of relevant policy instruments on the costs of emitting CO₂ and other GHGs, incentives for the introduction of renewable fuels and electricity generation. Using this approach, it is possible to calculate the influence of these system changes on global CO₂ emissions.

The timeframe for the utilisation options for IEH in this study include long-term investments, with an economic lifetime of at least 20 years. For this reason, future energy-market scenarios for 2030 and 2040 are required. To build these scenarios, ENPAC takes as input the possible evolution of fossil fuel prices and CO₂ emission charges between now, 2030 and 2040. For this purpose, scenarios presented in the report World Energy Outlook (WEO) 2020 from the International Energy Agency (IEA) were considered [119]. The report presents three scenarios: Stated Policies (SP), Delayed Recovery (DR) and Sustainable Development (SD) [119]. The SP scenario incorporates today's policy intentions and targets, and an assumption that the Covid-19 situation is gradually brought under control and the global economy returns to pre-crisis levels during 2021. The DR scenario makes the same assumptions as the SP scenario but incorporates a prolonged pandemic situation, with the global economy returning to pre-crisis levels during 2023. Finally, the SD scenario maps out a way to meet sustainable energy goals in full, including the Paris Agreement, energy access and air-quality goals. This requires rapid and widespread changes across all parts of the energy system.

Table 9 shows the inputs for these energy-market scenarios and the resulting scenarios for the years 2030 and 2040.

Possible build margin technologies for electricity production embedded in the ENPAC tool are coal-fired power plants and natural gas combined cycle (NGCC) plants (with and without carbon capture and storage (CCS)), nuclear power and wind power. In building the scenarios, nuclear power is allowed as a build margin technology for 2030 only in the SD scenario, and in 2040 for all scenarios. Policies to support CO₂-neutral technologies in the SD and SP scenarios justify why nuclear power is allowed for marginal electricity production in the European context. Wind power is considered to be available as a build margin in all scenarios, except for SD-2040, because it is assumed that the available sites for installation will have been exhausted by that year, and no further large-scale potential for installation is available. The economic evaluation was performed by considering the unit costs of heat and electricity supply given by the three energy-market scenarios, over the economic lifetime of the investment. Total costs include investment costs, operation and maintenance costs and capital costs, discounted by the revenues from heat and electricity sales.

When biomass is not considered to be a limited resource, the burning of biomass is seen as CO₂ neutral, and only includes emissions from harvesting, transport, etc. On the other hand, when biomass is considered a limited resource, competition for this resource is included in the analysis. The consequence is that, if the demand for biomass increases in the system, the marginal (i.e., price-setting) user of biomass has a deficit in supply and must therefore use another energy carrier instead. The price-setting user is assumed to be either a coal-fired power plant with the capability of co-firing some wood fuel with the fossil coal (thus fossil coal consumption is affected) or a producer of biofuel for transportation (thus gasoline or diesel consumption is affected) [118].

Table 9. Scenario inputs [119] and resulting energy prices and emission factors for the countries studied. Pellets = Co-firing coal power plants. Charcoal = pig iron production.

Scenario inputs										
Year		2025			2030			2040		
Energy-market scenario		SD	SP	DR	SD	SP	DR	SD	SP	DR
Crude oil price (USD/barrel)	All	57	71	59	56	76	63	53	85	72
Natural gas price (USD/Mbtu)	SE, UK	5	7	6	5	8	7	5	8	8
	BR	6	8	8	6	8	8	6	9	8
Steam coal price (USD/tonne)	SE, UK	57	66	60	56	71	61	55	68	64
	BR	73	83	76	71	83	75	67	79	73
CO ₂ emission charge (EUR/tonne)	SE, UK	56	30	30	79	36	36	125	46	46
	BR	43	0	0	70	0	0	125	0	0
Renewable electricity certificates (EUR /MWh)	SE	5	5	5	5	5	5	0	0	0
	UK	10	10	10	10	10	10	5	5	5
	BR	0	0	0	0	0	0	0	0	0
Biofuel support (EUR /MWh)	SE, UK	54	54	54	36	36	36	18	18	18
	BR	0	0	0	0	0	0	0	0	0
Allow CCS for marginal electricity production	All	No	No	No	No	No	No	Yes	Yes	Yes
Allow nuclear power for marginal electricity	SE, UK	No	No	No	Yes	No	No	Yes	Yes	Yes
	BR	No	No	No	No	No	No	No	No	No
Allow wind power for marginal electricity	SE, UK	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes
	BR	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Biomass limited resource	All	No	No	No	Yes	No	No	Yes	No	No
Resulting scenarios										
Build margin technology for electricity generation	SE	Wind	Coal	Coal	Wind	Wind	Wind	Nuclear	Wind	Wind
	UK	Wind	Coal	Coal	Nuclear	Wind	Wind	Nuclear	Wind	Wind
	BR	Wind	NGCC	NGCC	Wind	Wind	Wind	Wind	Wind	Wind
Price of electricity (excluding grid costs and taxes) (EUR /MWh _{el})	SE	45	53	51	45	45	45	54	49	49
	UK	39	53	51	54	39	39	54	44	44
	BR	49	59	57	49	49	49	49	49	49
CO ₂ emissions from marginal electricity production (kg CO ₂ /MWh)	SE	0	856	856	0	0	0	0	0	0
	UK	0	856	856	0	0	0	0	0	0
	BR	0	394	394	0	0	0	0	0	0
Marginal (price setting) user of wood fuel	SE, UK	Pellets								
	BR	Charcoal								
Price of low-grade wood fuel (EUR /MWh _{fuel})	SE	18	10	9	26	12	11	40	13	13
	UK	20	12	11	29	15	14	42	16	16
	BR	39	21	20	51	21	20	75	20	19
CO ₂ reduction from marginal use of biomass (kg CO ₂ /MWh _{fuel})	SE, UK	47	21	21	405	47	47	405	47	47
	BR	47	35	35	405	47	47	405	47	47

4.3 Economic evaluation

The economic evaluation was performed by considering the heat and electricity costs given by the energy-market scenarios (as in Section 4.2.1), over the economic lifetime of the investment. For consistency with the energy-market scenarios in ENPAC, economic calculations were performed for the lifecycle costs (LCC) of the equipment. Total costs include investment costs, operation and maintenance costs and capital costs, discounted by the revenues from heat and electricity sales. To account for the economic lifetime of equipment and capital costs, the capital recovery factor (CRF, Eq. (7)) was used to annualise the investment costs (I) over the economic lifetime (N_L) using the interest rate (i). The net present value (NPV, Eq. (8)) of the investment over the economic lifetime (N_E) was then calculated by considering the annual cash flows (CF_n) for a discount rate (d), with the electricity, heat and fuel costs and the certificates for renewable electricity calculated according to the scenario results from ENPAC. The economic lifetime considered was 20 years, with a discount rate of 5% for all cases, in line with the recommendations of the European Commission for the analysis of energy investment projects [120]. The loan period considered was five years, with a 5% interest rate.

$$CRF = \frac{i(1+i)^{N_L}}{(1+i)^{N_L} - 1} \quad (7)$$

$$NPV = \sum_{n=1}^{N_L} (CRF_n \cdot I) + \sum_{n=1}^{N_E} \frac{(CF_n)}{(1+d)^n} \quad (8)$$

4.3.1 District heating deliveries

Investment costs for delivering IEH to a DH network were estimated as the costs for piping plus the costs of the heat exchangers required to collect the heat at the mill. The costs for installing the heat recovery system at the mill were estimated as an average of the costs presented by Eriksson et al. [121], who calculated investment costs for heat exchanger installation at a chemical cluster recovering heat for excess heat deliveries for DH networks. The temperatures considered in that study are similar to those used in this thesis. Operation and maintenance costs were assumed to be 1.5% of investment costs. Connection distances of between 1 and 100 km were considered. Because the costs for pipe installation vary with the heat delivery capacity, a range of capacities between 5 MW and 200 MW was included in the estimation, to account for the heat available in the case studies. The costs of operation and maintenance of the network were assumed to be 1% of investment costs. Figure 12 shows the total cost for implementing the heat delivery system at varying heat delivery capacities. Table 10 summarises the costs associated with direct heat deliveries.

Figure 12. Investment costs for the heat delivery systems considered, including heat exchanger network installation costs and delivery pipes at distances varying from 1 km to 100 km, at different delivery capacities.

Table 10. Investment, operation and maintenance costs for the heat recovery technologies studied.

	DH	
	Heat recovery system	Piping
Investment costs (EUR/kW)	562	11–140*
Operation and maintenance costs (% of investment costs)	1%	1.5%

*The investment costs for piping are in the range of 5 MW to 200 MW of delivery capacity and are per metre of piping.

4.3.2 Organic Rankine cycle equipment

In line with similar studies, an operation and maintenance cost of 2% of the investment costs was used, excluding fuel costs [39,54]. Specific investment costs were adapted from Bühler et al. [39], Johansson and Söderström [54] and Quoilin et al. [122], which resulted in the costs shown in Figure 13. The costs for the heat exchangers to connect the ORC equipment to the process are not considered.

Figure 13. Specific investment costs and total investment costs. Based on data from [39,54,122].

5

Results and analysis

This chapter first presents and analyses the results obtained for the availability of IEH in the case studies and the estimation of electricity generation potentials from low and medium temperature IEH using ORCs. The chapter continues with the results from the regression analyses for electricity generation potentials and excess heat availability. The final sections present the CO₂ emissions balances and the economic analysis, ending with a comparison of the application of ORCs in different energy markets and conditions.

5.1 Excess heat availability and excess heat temperature signatures

Figure 14 presents the estimated theoretical and process cooling XHT signatures together, for each of the six case studies. The excess heat available for the process cooling conditions tends to follow the curve for the theoretical heat integration conditions, except for the Karlsborg case, in which the process cooling XHT signature shows a much larger availability of excess heat. These results also show that the availability of excess heat at high temperatures is limited in kraft pulp mills, with only the Karlsborg case showing higher availability of latent heat at 140°C. Overall, the availability of medium to high temperature excess heat tends to be greater for the process cooling condition than for the theoretical heat integration case, due to the increased internal heat recovery in the latter. The total availability of IEH for the six case studies is shown in Table 11. In general, the availability of heat is greater in the process cooling XHT signature, which is expected.

Table 11. Total availability of IEH for the six case studies, by temperature level.

Temperature (°C)	Theoretical XHT signature (MW)	Process Cooling XHT signature (MW)
≥140°C	3	168
>100°C	10	189
≥100°C	122	253
>60°C	227	392
≥60°C	388	457
>40°C	665	513
≥40°C	722	937
>25°C	722	937

Figure 14. Theoretical and process cooling XHT signatures considering annual IEH availability (operating for 7834 hours/year in steady-state operation and with seasonal variations ignored): a) Södra Värö; b) SCA Östrand; c) Holmen Iggesund; d) Billerud-Korsnäs Karlsborg; e) FRAM typical pulp mill; f) FRAM typical integrated mill.

To make a direct comparison between the six case studies easier, Figure 15 shows the process cooling XHT signature, which represents the heat availability for each of the case studies, at each of the temperature levels considered. The largest proportion of the heat availability occurs at temperature levels which are too low for either electricity generation or direct deliveries to DH networks.

Figure 15. Excess heat (XHT) signatures for the six case study mills.

To visualise the excess heat availability at different temperature levels as a function of the energy input to the process, Figure 16 presents a comparison of the specific excess heat availability between the six mills compared to energy input to the process, both for the estimated total excess heat ($\geq 25^{\circ}\text{C}$) and for temperatures $> 60^{\circ}\text{C}$. Overall, the total availability of excess heat varies significantly between the case studies, but integrated pulp and paper mills have a lower availability of excess heat than market pulp mills, due to the extra energy requirements of the drying process for the paper product. However, the availability of excess heat above 60°C is much less than the total excess heat available ($\geq 25^{\circ}\text{C}$), being less than 15% of biofuel energy use in most cases. Above 60°C , the availability of excess heat under process cooling conditions is much greater than in the theoretical scenario. This is an indication that pulp and paper mills can deliver larger amounts of excess heat if running under process cooling conditions, and that these mills are more likely to deliver avoidable excess heat.

In the case of Södra Östrand, the availability of IEH is much greater than for the other mills. This could indicate that modern mills are more likely to deliver larger amounts of excess heat. This case, however, is based on quotations from experts and typical values, and not direct measurements; hence, there is more uncertainty about these results. The FRAM typical mills show a lower availability of excess heat than the real mills, potentially because a more detailed analysis of the heat demands and heat sources in the process was carried out than was achievable in the studies of the real mills. For the real mills, there may have been different constraints in the collection of data for the thermal stream for practical reasons. If that is the case, the theoretical excess heat estimated for the four real mills is likely to have been an overestimate, whereas the process cooling excess heat would be underestimated for the FRAM mills.

Figure 16. Estimated specific excess heat availability. The numbers show the fraction of declared biofuel energy usage that is available as excess heat above 25°C (left) and above 60°C (right) in the six kraft mills studied.

5.2 Regression analysis for excess heat availability

Figure 17 presents the availability of excess heat above 60°C together with the results of the linear regression analysis (68% confidence interval) for the six case studies. Because the availability of excess heat is lower at this temperature level and varies broadly between the case studies, the confidence intervals associated with the estimates are large (as shown in Figure 17), and become larger for higher temperatures, at which heat availability is more limited and differs significantly between the different mills. Complete regression results are available in Tables A1 and A2 in Paper 2. In general, it is noted that results for the linear regression coefficients calculated for Eq. (3) (see Section 4.1.4) are higher for the market pulp coefficients (m) than for the paper coefficients (n) (see Tables A1 and A2 in Paper 2). This is consistent with the greater availability of excess heat in market pulp mills than in integrated mills, as mentioned previously. The total IEH available if the regressed XHT signatures for all kraft mills are summed up is shown in Table 12.

Table 12. Sum of the regressed XHT signatures for all kraft mills in Sweden.

Temperature (°C)	Theoretical XHT signature (MW)	Process Cooling XHT signature (MW)
≥140°C	89	3 469
>100°C	309	4 214
≥100°C	3 594	5 845
>60°C	5 544	9 081
≥60°C	9 020	9 773
>40°C	15 775	11 009
≥40°C	16 412	20 264
>25°C	16 412	20 264

Figure 17. Estimated and regressed results for the availability of excess heat above 60°C for the six kraft mills. The error bars are the 68% confidence intervals.

5.3 Low and medium temperature electricity generation and DH deliveries for the case studies

The estimated values for low and medium temperature electricity generation with ORC are shown in Table 13 for the IEH availability estimated from the theoretical XHT signatures and in Table 14 for the IEH availability estimated from the process cooling XHT signatures. These results are based on the integration of electricity generation with ORC technology directly from the estimated IEH availability (XHT signature), and not the regression results, which are presented later. The percentage increase in electricity production is calculated on the basis of the integrated steam cycle that was targeted for each mill. The totals for all mills are based on the declared electricity production of each kraft mill in Sweden. The estimation based on the theoretical XHT (Table 13) shows that most mills in the case studies can increase their targeted electricity generation by 3–7% in a theoretical scenario where bark use is minimised, typically by utilising low and medium temperature IEH. The exceptions are Iggesund and the FRAM typical integrated mill, which had relatively low electricity generation targets from conventional back-pressure turbines of 21 GWh/a and 88 GWh/a respectively (see Table 13). The adoption of low and medium temperature electricity generation could theoretically increase electricity generation by 129% in Iggesund and 28% for the FRAM typical integrated mill. These are both integrated mills, which, as mentioned previously, have a lower availability of high-temperature heat from the recovery boiler to be used for cogeneration in back-pressure turbines. The Iggesund mill was also the integrated mill with the highest availability of excess heat (see Figure 17), so the very high potential increase in electricity generation is an expected result. On average, the potential for increasing electricity production in the six case studies is 7%.

The estimation of electricity generation for the process cooling scenario shows less variation in the potential to increase electricity production across the six case studies when compared to the theoretical scenario. In this estimation, the mills have a higher availability of steam due to accounting for bark use, which is partly used to produce electricity in back-pressure and condensing turbines. The greater increase in low and medium temperature electricity generation in the case of Karlsborg is related to the much higher availability of excess heat in the process cooling scenario for this mill (see Figure 14). In the estimation of medium and low temperature electricity generation in the process cooling scenario, the average potential increase in electricity production in the mills is 9%. Note that the references for the increase in electricity generation potential as a percentage are taken individually from the estimated electricity generation potentials from conventional steam cycles, which are much higher in the process cooling scenario than in the theoretical heat integration scenario. In fact, the estimated potential for electricity generation from ORC using IEH in the process cooling scenario is 33% higher than in the theoretical heat integration scenario (254 GWh/a versus 190 GWh/a, respectively).

Table 13. Estimated annual electricity generation potential from low and medium temperature industrial excess heat in the six case studies for the theoretical heat integration scenario.

Temperature level	Electricity generation (GWh/a)						Total (cases)
	Södra Cell Värö	SCA Östrand	Holmen Iggesund	Billerud-Korsnäs Karlsborg	FRAM type pulp mill	FRAM type integrated mill	
ORC 60	37	19	21	0	24	20	121
ORC 100	0	52	6	4	0	5	67
ORC 140	0	0	0	2	0	0	2
Total (mill)	37	71	28	6	24	25	190
Integrated steam cycle	565	1 340	21	205	393	88	2 612
Increase in electricity production ¹	7%	5%	129%	3%	6%	28%	7%

¹ The reference electricity production for calculating the increase in production is the integrated steam cycle targeted for each mill in the scenario considered.

The calculated heat delivery capacities to DH networks for each of the case studies is shown in Table 15, considering a DH return temperature of 46°C and network supply temperature of 86°C. This calculation is shown only for the process cooling conditions, as only the values for this case are used in the economic calculations in Section 5.6.

Table 14. Estimated annual electricity generation potential from low and medium temperature industrial excess heat in the six case studies for the process cooling heat integration scenario.

Temperature level	Electricity generation (GWh/a)						Total (cases)
	Södra Cell Värö	SCA Östrand	Holmen Iggesund	Billerud-Korsnäs Karlsborg	FRAM type pulp mill	FRAM type integrated mill	
ORC 60	34	40	19	0	0	0	93
ORC 100	0	35	2	6	0	6	48
ORC 140	0	55	1	19	25	13	113
Total (mill)	34	129	21	25	25	19	254
Integrated steam cycle	631	1 342	250	192	260	281	2 956
Increase in electricity production ¹	5%	10%	8%	13%	10%	7%	9%

¹ The reference electricity production for calculating the increase in production is the integrated steam cycle targeted for each mill in the scenario considered.

Table 15. Calculated heat delivery capacity for the six case studies.

Mill	Heat delivery capacity to DH networks (MW)
Södra Cell Värö	38 375
SCA Östrand	245 387
Holmen Iggesund	40 440
Billerud-Korsnäs Karlsborg	38 895
FRAM market pulp mill	37 623
FRAM type integrated mill	29 792

5.4 Regression analysis for low and medium temperature electricity generation

Table 16 presents estimated electricity generation potentials from low and medium temperature excess heat for each temperature level considered. It compares the potentials for the case study mills estimated either by using their XHT signatures, or by using the regression models of their excess heat availability. Table 11 also presents the total potential estimated for all kraft mills in Sweden using the regression model for excess heat availability in each mill. A comparison between the estimation based on the actual theoretical XHT signatures and an estimation based on the regressed theoretical XHT signatures for the case studies shows very similar results, with the potential to increase electricity production in the case study mills by 7% over the power generation targets for integrated steam cycles (see Table 13). When considering the totals for all mills in Sweden, the regressed values result in a potential increase of 10% in electricity production, probably with an over-estimation of the potentials at higher temperatures (ORC 100 and ORC 140), due to the greater uncertainties at these temperature levels in the regressed excess heat availability. The electricity generation potential from the regression analysis for each of the mills in the theoretical scenario is shown in Table B1 in Paper 2.

Table 16. Comparison between estimated electricity generation potentials from low and medium temperature IEH and regressed potential, plus total generation potentials for all kraft mills in Sweden (theoretical scenario).

Temperature level	Estimated total, case studies (GWh/a)	Regressed total, case studies (GWh/a)	Regressed total, all Swedish kraft mills (GWh/a)
ORC 60	121	103	275
ORC 100	67	80	251
ORC 140	2	2	8
Total (mills)	190	185	534
% increase	7%	7%	10%

Table 17 presents the results of the regression analysis, but for the process cooling scenario. As with the theoretical scenario, the results for the individual estimation at each temperature level are similar. In the process cooling scenario, the regressions for a few of the smaller integrated mills resulted in negative excess heat in some of the higher temperature intervals. This is a consequence of the very large negative constant coefficients (k) and smaller paper coefficients (n) in the regression functions (see Tables A1 and A2 in Appendix A). In the temperature intervals with negative availability of excess heat, no excess heat was added to the XHT signature at that temperature level. The regressed values indicate a potential increase of 9% in electricity production. The electricity generation

potential from the regression analysis for each of the mills in the process cooling scenario is shown in Table B2 in Paper 2.

Table 17. Comparison between estimated electricity generation potentials and regressed potentials, plus total generation potentials for all kraft mills in Sweden (process cooling scenario).

Temperature level	Estimated total, case studies (GWh/a)	Regressed total, case studies (GWh/a)	Regressed total, all Swedish kraft mills (GWh/a)
ORC 60	93	100	224
ORC 100	48	59	177
ORC 140	113	119	289
Total (mills)	254	278	690
% increase	9%	9%	13%

5.5 CO₂ emissions balances

The base cases presented in this section consider the following: electricity production operating the same number of hours as the kraft mill (7834 hours/year); DH deliveries replacing HOB for 25% of the mill's operating hours in a year; and DH deliveries replacing CHP for 35% of the mill's operating hours in a year.

The results for the CO₂ emissions balances are presented in Figure 18, in kilograms of global CO₂ emission reductions per megawatt-hour of heat delivered. For electricity production using ORC technology, the figures presented are for global CO₂ emission reductions during the 20-year economic lifetime of the equipment, and assuming that the electricity produced would replace the build margin for each year of operation (see Table 9). The results show that for all cases there is a reduction in global CO₂ emissions. Overall, electricity generation is more favourable than DH deliveries for the SP and DR scenarios, while DH deliveries are more beneficial in the SD scenario. Electricity production has an advantage in the SP and SD scenarios because, until 2025, the electricity build margin in the ENPAC scenarios is coal-fired power plants. In the SD scenario, wind power has already become the build margin by 2025, and consequently the lifetime emissions reduction is smaller. Comparing the two options to replace DH production, IEH replacing a HOB is more favourable than when replacing a CHP plant for the SP and DR scenarios, but performs slightly worse in the SD scenario. The reasons for this are that replacing heat production in HOB releases biomass for co-firing in coal plants until 2025, whereas the replacement of heat production in CHP plants in these two scenarios reduces electricity generation from the CHP plant, which in turn needs compensation from the build margin (coal-fired power plant) until 2025. In the SD scenario, DH deliveries replacing CHP become more favourable than replacing a HOB because the emissions from electricity production in this scenario are already zero from 2025 (build-margin is wind power), and the biomass released for marginal uses has the largest CO₂ reductions of all in this scenario (see Table 9).

Figure 18. Lifecycle-specific CO₂ emission reductions of electricity production and DH deliveries, divided into deliveries substituting for HOB or CHP plants.

Figure 19 presents the results for each of the case studies, in total global CO₂ emission reductions over the economic lifetime of the heat recovery equipment installed. These results reflect those presented for the specific emission reductions, with the obvious difference that the cases with larger heat availability have larger potential for total emission reductions. One important difference to note is that, in the base case, ORCs run during the same number of hours as mill operations, while DH deliveries only occur for 25% (HOB) and 35% (CHP) of the mill's operating hours. Because of this difference in operating hours, DH deliveries result in lower reductions in CO₂ emissions than the real potential. The results presented consider the amount of heat recovered, ignoring thermal losses in the DH network.

Figure 19. Lifecycle CO₂ emission reductions due to electricity production and DH deliveries, divided into deliveries substituting for HOB or CHP plants, for the six case studies. Base case: electricity production operating for the same hours as the kraft mill; DH deliveries replacing HOB for 25% of the mill operating hours in a year; and DH deliveries replacing CHP for 35% of the mill operating hours in a year.

5.6 Economic analysis

The base cases presented are the same as those in Section 5.5, with these additional assumptions: a connection distance to the DH network of 1 km, a discount rate of 5%, an interest rate of 5% and a loan period of 5 years. The results are also presented with the investment costs for the heat collection network either excluded or included.

The net present values (NPV) are presented in Figure 20 in EUR/MWh_{heat} recovered for the base case with investments in the heat collection network excluded. In contrast to the CO₂ emissions balances, electricity production from IEH is less profitable per unit of heat recovered than DH deliveries. Nevertheless, all the base cases show positive NPV for all ENPAC scenarios. Comparing the three options between scenarios, the profitability of electricity production shows only a small variation. When looking at DH deliveries, the SD scenario is up to 100% more profitable than either the SP or DR scenarios. This happens because biomass prices become higher in the SD scenario, which in turn makes heat production in HOB and CHP more expensive and the willingness to pay for IEH increases. This improves the revenue from heat sales for the DH delivery cases in the SD scenario. It is important to note that, in this base case, the ORC has the same operating hours as the mills, while DH deliveries only deliver heat for 25% (HOB) and 35% (CHP) of the operating hours of the plants.

Figure 20. Specific net present value (NPV) of investments in electricity production and DH deliveries, divided into deliveries substituting for HOB and CHP plants. Base case: electricity production operating the same hours as the kraft mill; DH deliveries replacing HOB for 25% of the mill's operating hours in a year; and DH deliveries replacing CHP for 35% of the mill's operating hours in a year. Heat recovery network costs are excluded.

The values presented in Figure 20 show the NPV excluding heat collection costs. If investment costs in the heat collection network are included (see Figure 21), DH deliveries show no profitability, except for DH deliveries replacing CHP plants in the SD scenario. The reasons for this are the same as in the previous case, i.e. biomass prices are high due to being a limited resource.

Figure 21. Specific net present value (NPV) of investments in electricity production and DH deliveries, divided into deliveries substituting for HOB or CHP plants. Base case: electricity production operating the same hours as the kraft mill; DH deliveries replacing HOB for 25% of the mill's operating hours in a year; and DH deliveries replacing CHP for 35% of the mill's operating hours in a year. Investment in the heat recovery network is included.

5.6.1 Sensitivity analysis

Several factors influence the economic feasibility of investments. To understand how different factors influence the feasibility of investing in the heat recovery options analysed previously, a sensitivity analysis is presented for the interest rate of the capital investments, the connection distance to the DH network, and the utilisation times of the available heat delivery capacity in the case of DH deliveries. The revenues generated by the different options for varying electricity and heat prices are already well covered in the different ENPAC scenarios. The figures are presented for the base case, varying only one parameter to highlight its effect on the results.

Figure 22 presents the NPV of the three utilisation options for interest rates of 5%, 10% and 15%. The profitability of electricity generation using ORC is more strongly influenced than DH deliveries due to the relatively low investment costs of the DH piping in these cases, considering that the investment costs of the heat collection network are excluded. Nevertheless, all investment options remain profitable for the interest rates considered. Figure 23 presents a similar analysis, but with the investment costs of the heat collection network considered. In this situation, the DH delivery options are less attractive. DH deliveries replacing a HOB are only profitable for an interest rate of 5% and in the SD scenario. DH deliveries replacing CHP heat production are profitable for all interest rates in the SD scenario, and also have higher NPVs than ORC electricity production.

Figure 24 shows how the utilisation time affects the profitability of the DH delivery option. The operation time of electricity generation with ORC is not varied and is shown only for reference. Increased utilisation times render the DH HOB and DH CHP cases profitable in the SP and DR scenarios, even when heat collection network costs are included. Higher utilisation times would mean that excess heat could act as a baseload during longer periods of the year. However, given the large amounts of heat available from kraft pulp and paper mills, this is unlikely to happen.

Figure 22. Sensitivity analysis for the economic evaluation of the heat recovery options. The interest rate of 5% in the base case is raised to 10% and 15%. Heat collection network costs are excluded.

Figure 23. Sensitivity analysis for the economic evaluation of the heat recovery options. The interest rate of 5% in the base case is raised to 10 and 15%. Heat collection network costs are included.

Figure 25 shows the sensitivity analysis for the connection distance of DH deliveries, with the NPV of ORC electricity production shown for reference. When the heat collection network costs are excluded, connection distances up to 50 km remain profitable in the SD scenario. For DH deliveries substituting for a HOB, the limit for profitability is 27 km and 32 km in the SP and DR scenarios, respectively. In the case of substitution for heat production in a CHP plant, these distances increase to 38 km (SP) and 44 km (DR). As shown in Figure 23, if the costs of the heat collection network are considered, none of the scenarios are profitable even at connection distances of 1 km, except for the SD scenario.

Figure 24. Sensitivity analysis for the economic evaluation of the heat recovery options. The utilisation time (heat delivery hours compared to mill operating hours) is raised from 25% to 50% and 100% in the HOB case, and from 35% to 80% and 100% in the CHP case. Heat collection network costs are included.

Figure 25. Sensitivity analysis for the economic evaluation of the heat recovery options. The connection distance from the mill to the DH network is varied from 1 km to 10 km and 50 km. Heat collection network costs are excluded.

5.7 Comparison of IEH recovery with small-scale ORC CHP

5.7.1 Economic feasibility of ORC technology in different applications and energy markets

To demonstrate the impact of different economic policy instruments and energy-market conditions, the results of the analysis are presented both with and without certificates for renewable electricity, electricity taxes and network costs.

The economic analysis shows that ORC systems could be profitable in all three countries studied (Figure 26), except for case BR1 in the SD scenario. Additionally, the size of the

ORC equipment has a significant impact on the profitability, showing that economies of scale are an important aspect to consider. With the assumptions made in the scenarios in ENPAC, considering the specific investment costs adopted and not account for the avoided costs and incentives, the smaller ORC machines (50 kW_{el}) in general only show profitability in the cases where IEH recovery is considered. ORC machines with a larger power output, i.e., 500 kW_{el} and higher, could be interesting investments in cases SE1, UK1 and BR1 even without considering the benefits of certificates for renewable electricity and avoided costs for taxes and grid costs. The exception is the case BR1 in the SD scenario, which shows no profitability for any equipment size.

Cases SE1, UK1 and BR1 incur extra biomass costs, which explains why the cases with IEH recovery (SE2, UK2, and BR2) are more profitable in general, because the excess heat is considered to be free of charge. In general, the most profitable scenario would be the installation of an ORC using IEH in Sweden, but the differences are not large in relation to the other cases of IEH recovery.

Figure 26. Economic analysis of the installation of ORCs of different sizes (electrical power output) in three countries, including CO₂ emission charge, but excluding certificates for renewable electricity, electricity taxes and network costs. The economic feasibility is shown as NPV per kW of electrical power installed. The economic results are shown for three scenarios taken from [119]: Sustainable development (SD), Stated policies (SP) and Delayed recovery (DR).

Figure 27 shows the results with country-specific economic policies (i.e., taxes and certificates for renewable electricity) and electricity network costs included in the analysis. For an installed electricity capacity below 100 kW, the electricity tax and network costs become avoided costs for the Swedish cases, while capacities above 100 kW_{el} pay electricity tax, but with a tax reduction to 0.5 EUR/MWh. For capacities above 1000 kW_{el}, it was assumed that 20% of the extra electricity generated is sold. In the UK and Brazilian cases, all the electricity is used in-house, and the companies pay no electricity taxes or network costs for the electricity produced. Sweden and the UK have certificates for renewable electricity production, which contributes to increased profitability. When comparing Figure 26 with Figure 27, it is possible to see that the profitability is greatly influenced by including the avoided costs for electricity taxes and network costs and income from certificates in the analysis. Including these avoided costs, all system sizes become profitable in all scenarios. For ORC units up to 100 kW_{el}, the tax exemption in

Sweden and avoided taxes and grid costs in Brazil and the UK compensate for the higher specific investment costs, and these units become profitable. For units larger than 100 kW_{el}, the profitability is also increased, improving the economic performance of ORC units in all scenarios. The biggest changes occur for the UK and Brazil cases, in which the avoided costs of higher taxes and grid costs increase the profitability by the largest amount. Case BR1 shows poorer profitability due to high biomass prices in this case, but is nevertheless profitable.

Figure 27. Economic analysis of the installation of ORCs of different sizes (electrical power output) in three countries, including CO₂ emission charge, certificates for renewable electricity, electricity taxes and network costs. The economic feasibility is shown as NPV per kW of electrical power installed. The economic results are shown for three scenarios taken from [119]: Sustainable development (SD), Stated policies (SP) and Delayed recovery (DR).

To visualise the effects of taxes, certificates and network costs in more detail, Figure 28 and Figure 29 show the cases SE1 and SE2, respectively, with and without taxes, certificates and network costs. As shown before, ORC systems of 50 kW show no profitability with revenue from certificates and avoided costs from taxes and network fees excluded, but become profitable when the avoided costs are considered. System sizes below 500 kW benefit the most from tax exemptions, and all equipment sizes are profitable. Figure 29 also shows that IEH recovery makes the profitability of ORC systems less sensitive to the energy market scenarios, as there is no biomass cost associated with ORC operation.

Figure 28. Economic analysis of the installation of ORCs of different sizes (electrical power output) for the SE1 case. The economic feasibility is shown as NPV per kW of electric power installed for the scenarios with and without certificates for renewable electricity, taxes and network fees in Sweden.

Figure 29. Economic analysis of the installation of ORCs of different sizes (electrical power output) for the SE2 case. The economic feasibility is shown as NPV per kW of electric power installed for the scenarios with and without certificates for renewable electricity, taxes and network fees in Sweden.

5.7.2 Carbon dioxide emissions balances of ORC technology in different applications and energy markets

The evaluation of how CHP production and IEH recovery using ORC systems would affect global emissions of GHG shows that emissions would decrease in all three countries and all the scenarios studied, except for cases SE1 and UK1 in the SD scenario (Figure 30).

Figure 30. Effect on global GHG emissions of the installation of ORCs in Sweden, the UK and Brazil, considering the lifetime of the ORC and assuming three future energy-market scenarios. The scenarios are based on the Sustainable development (SD) scenario, the Stated policy (SP) scenario, and the Delayed recovery (DR) scenario in World Energy Outlook 2020 [119]. The emission reductions are shown as CO₂-eq per kW of electrical power installed.

The results for emission reductions are the same for the SP and DR scenarios, where the Swedish and UK cases have equal values, because in these two scenarios biomass is not considered a limited resource. In the SP and DR scenarios, the Brazilian case would yield lower reductions. The reason for this is that in the Swedish and UK cases the electricity that is produced would replace electricity production in coal-fired power plants up to the year 2025, while for the same period in Brazil the electricity production replaces power generation by NGCC, which is less carbon intensive. In the SD scenario, the reduction in emissions is less pronounced than for the other cases, and even results in an increase in global CO₂ emissions in cases SE1 and UK1 cases. This is explained by the fact that the electricity that is produced by the ORC in Sweden, the UK and Brazil replaces carbon-neutral electricity from wind or nuclear from 2025 onwards. In the SD scenario, biomass is considered a limited resource from 2030 onwards. This implies that there is a CO₂ emissions penalty attached to the increased demand and use of biomass. This penalty equates to the emissions that the marginal biomass user emits as a result of using fossil fuels instead of biomass. In the Swedish and UK cases, the marginal biomass user is a coal-fired power plant substituting pellets for some of its fossil coal and in the Brazilian case the marginal user is an iron and steel plant using charcoal instead of fossil coke. As no extra biomass is used in cases SE2, UK2 and B2 cases, there is no CO₂ emissions penalty for using biomass.

6

Discussion

This chapter discusses the main results of this thesis.

6.1 Heat integration and excess heat availability

The heat integration analysis was divided into two scenarios. The theoretical heat integration aimed to determine the availability of IEH in kraft pulp and paper mills as a lower bound estimation of excess heat availability, in what can be considered unavoidable excess heat. Any amount of IEH above the theoretical potential can be considered avoidable excess heat, at least in a thermodynamic sense [111]. To assess the current availability of excess heat at all Swedish kraft mills, the process cooling heat integration scenario included technical assumptions, such as non-zero ΔT_{min} driving temperatures for heat exchange, lower steam turbine efficiencies and constraints in heat integration, such as the presence of a secondary warm and hot water system. Additional assumptions had to be made for the process cooling scenario, the most relevant being the estimation of the amount of bark used in the mills. These estimations include uncertainties related to the steam header properties, different types of raw material used in the pulp process, such as hardwood or softwood, and the quality of the biofuel used. Also, the load of the mill in relation to the actual production capacity and operating hours, and the quality of the data reported by the companies were considered. Nevertheless, the results should indicate representative values.

The electricity generation targets from conventional steam turbines have a large effect on the availability of excess heat in a mill. Figure 31 compares the electricity generation targets from conventional steam turbines with the values declared by the companies in the online database used. When considering the process cooling scenario, the declared generation is close to or exceeds the conventional electricity generation estimated for the mills, except for the case of Södra Cell Värö. This indicates that the assumptions made for the process cooling scenario in this study are actually conservative. Note that, for SCA Östrand, the estimations were based on a planned reconstruction of the mill, and declared electricity generation figures for the reconstructed mill are currently unavailable.

The specific IEH availability found in the six case studies (Figure 16) shows that, for most cases, the excess heat available above 60°C is less than 15% of the biofuel energy input to the process. This figure is much lower than that used in broad studies based on basic sector efficiencies. For example, Persson et al. [32] used a figure of 25% recovery potential from the pulp, paper and printing sector for excess heat compatible with district heating (DH) applications. Beer et al. [123] studied energy efficiency in the pulp and paper sector in

Germany and reported that excess heat recovery potentials could result in steam savings of 9.3% on average, and up to 25%. In another study on pulp and paper mills in Germany, Fleiter et al. [124] reported 21% fuel savings through energy efficiency measures, and although this figure includes other efficiency measures, IEH recovery is regarded as the most important. These studies, however, considered the whole pulp and paper sector, including mechanical and recycled pulp, which have very different energy profiles. The differences in excess heat availability are also related to the differences in scope and limitations of the studies. While it is assumed in this paper that excess low-pressure steam is used in condensing turbines (unless such turbines would be too small), other studies probably include this as excess heat. Finally, kraft pulping is not as prevalent elsewhere, e.g. in Germany, as it is in Sweden. Nevertheless, the results obtained here provide more detail about IEH availability and temperature profiles, which are very useful in analysing the integration opportunities of specific technologies.

Figure 31. Specific conventional steam turbine electricity generation estimated in this study and declared values from [81]. Percentages shown as ratios of electricity production and biofuel usage. *The estimation for Östrand was based on quotations for a planned reconstructed mill, which only entered operation recently. Declared electricity generation after the reconstruction is currently unavailable.

6.2 Electricity generation from low and medium temperature IEH

The results presented for the electricity generation potentials of the different ORC systems are estimations of the technical potential of the power-generation technologies. The estimations for the process cooling scenario represent generation potentials that are probably close to those of the real mills, given the assumptions based on conditions that are normally found in Swedish kraft mills. The results for the theoretical scenario give a lower-bound estimate for what could be achieved in terms of electricity generation from low and medium temperature IEH.

The study considered that multiple ORC systems could be installed and operated simultaneously at different temperature levels to maximise electricity generation from IEH. In an actual implementation, this is unlikely to be the case, and one temperature level with optimal efficiency would be chosen. This is because practical considerations would prevent such arrangements of multiple ORC units operating at different temperature levels, especially the complexity of installation, considerations relating to investment costs and economic performance. Competition with other heat-recovery technologies is another factor to be considered, such as direct heat deliveries to district heating networks, or the integration of heat pumps into the process to increase the quality of the heat. Heat pumps are common in DH systems in Sweden, and low temperature IEH could even be used in connection with heat pumps to supply DH at temperatures that are lower than those required for many industrial processes. In fact, direct heat deliveries from the Swedish pulp and paper industry have increased slightly over the years (see Figure 2). However, not all mills have a heat demand nearby, highlighting the need to analyse alternative uses for the excess heat to enable an increase in energy and resource efficiency in industry. One particularly interesting result is that a considerable amount of the electricity generation potential is present at 60°C: about 50% in the theoretical heat integration scenario, and over 30% in the process cooling scenario. This temperature is generally too low to be used in typical Swedish DH networks, but the introduction of fourth-generation DH networks will allow such supply temperatures and could increase the utilisation of IEH.

6.3 CO₂ emissions balances and economic analysis

The ORC systems showed profitability in several of the studied contexts, with less interference from external conditions than experienced by DH deliveries. The greatest uncertainty affecting the analysis for DH deliveries is whether to include investment costs for the heat-collection network at the kraft mills. A precise estimation of costs for these heat-collection networks is very difficult and needs to be done on a case-by-case basis, especially if heat exchanger network retrofits are to be considered. Kraft mills normally have secondary heating networks that can potentially, in some cases, be directly connected to a DH delivery point. This would significantly reduce investment costs. If the costs for heat collection can be reduced, or if utilisation times greater than 50% of mill operating hours are possible, DH deliveries are likely to be significantly more profitable than ORC electricity production. The availability of large amounts of heat in kraft mills means that, even if a DH network exists near the mill, that network might not need all the excess heat available. In these cases, the introduction of ORC electricity generation has been shown to be profitable in all scenarios, and with fewer uncertainties regarding costs and energy-market scenarios. The sensitivity analysis showed that ORC electricity production is not strongly affected by higher interest rates, as opposed to DH deliveries with the cost of the heat collection network included. This is because the total investment becomes larger in the latter case.

The profitability of ORC systems has also been shown for IEH recovery and ORC CHP production. It was shown that incentives in the form of electricity certificates and tax reductions have a large impact on the profitability of smaller ORC systems, due to the higher specific investment costs for smaller equipment size. In kraft mills, these smaller systems are not relevant, but the comparison presented in Section 5.7 shows that IEH recovery is very favourable for the profitability of ORC systems, and ORC CHP also shows

economic potential when avoided costs and incentives are considered. This is in line with previous studies [125–128], which have shown that electricity production from industrial excess heat using ORC could be economically feasible. However, other studies have shown that such installations would not be profitable, mainly due to the low efficiency value [129] and the costs of cooling water and a refrigeration system [130]. The results show that a configuration in which the heat from the ORC condenser is used elsewhere (e.g., to heat the return flow in a DH system) affects the economics in a positive way, but the results obtained here show that IEH recovery is even more beneficial. Previous research [131,132] also confirms that electricity production using ORC at a biomass-fired co-generation plant for heat, cooling and electricity could be profitable. However, the economics depend to a large degree on the price of electricity [132,133], especially when considering avoided tax and network costs.

In terms of global CO₂ emissions, it is especially advantageous to produce electricity using an ORC system in settings where biomass is not a limited resource and industrial excess heat is available. DH deliveries also result in emission reductions, especially in the cases where biomass is limited, and DH deliveries replacing heat production in a HOB achieve larger reductions on average. In this thesis, no allocation of CO₂ emissions was made for the IEH recovered in the kraft pulp and paper mills. However, these mills do use a small amount of fossil fuels (see Table 5), and thus some allocation of emissions is required in a more detailed analysis, e.g. by allocating emissions to the proportion of excess heat that could be avoided if the process were thermodynamically optimised, as proposed by Pettersson et al. [117]. The calculation of global CO₂ emissions and economic performance from IEH recovery for electricity production and DH deliveries in the six case study mills was conducted for the process cooling scenario, which represents the current utility demands of the mill process. The ideal level of recovery of IEH would be the heat available after the process is optimised for maximum internal heat recovery. In this situation, the delivery of excess heat competes with the improvement of energy efficiency in the mill.

Small-scale electricity production, from biomass or industrial excess heat, using an ORC would reduce global emissions of GHG in all the cases studied, except in the SD scenario for the cases in Sweden and the UK that use biomass in CHP (SE1 and UK1). The size of these reductions depends to a large extent on the electricity production that would be replaced and whether wood fuel is a limited resource. These results are in line with previous studies, which have identified the same factors as key elements in how industrial heat deliveries to DH systems would affect global GHG emissions [13,117], and how a fuel switch in the iron and steel industry would impact upon global CO₂ emissions [79].

7

Conclusions

This chapter presents the conclusions from the research carried out. Conclusions are presented for each of the research questions.

In this thesis, a methodology has been presented to estimate the feasible technical potential for electricity generation from low and medium temperature industrial excess heat using ORC technology. The methodology is based on an analysis of the heat integration opportunities in individual kraft pulp and paper mills, in which the availability of excess heat for individual sites is estimated using detailed excess heat temperature profiles (XHT signatures). The results for individual sites using XHT signatures, combined with publicly available data for the pulp and paper sector at a national level, made it possible to estimate aggregated results for the whole sector using regression models. Based on such an approach, this thesis estimated national potentials for electricity generation from low and medium temperature excess heat. It was shown that, compared to estimated current levels of electricity production in the kraft pulp industry, there is a technical potential to increase electricity production by 7% or 9%, compared to scenarios which evaluate optimal steam-cycle integration under theoretical and process cooling conditions, respectively. The estimations were carried out for different temperature levels: 60°C, 100°C and 140°C, and thus present a more detailed account of excess heat recovery potentials than other studies which have aimed to estimate potentials for whole sectors.

The methods presented here could be adapted for other sectors and regions to obtain more detailed excess heat estimations, which in turn could help to guide strategies for the recovery and use of excess heat in different regions and different industrial sectors.

RQ1: How can the electricity generation potential using excess heat from an industrial process be estimated?

This thesis presented a procedure for estimating excess heat availability in kraft mills. The combination of pinch analysis and an energy-targeting methodology that provides a realistic overview of the energy balance of kraft mills in Sweden was the first step in obtaining the excess heat availability in an industrial process. The XHT signatures obtained allow for the estimation of electricity generation potentials using ORC technology. Although in this study particular attention was given to the possibility of generating electricity, any other heat-recovery method can also be analysed using the same procedure. This was exemplified in this thesis with the option of direct heat deliveries to DH networks. The aggregation of excess heat availability at defined temperature levels for different plants in the same sector is beneficial for understanding the excess heat availability in that sector.

RQ2: What is the availability of industrial excess heat and the electricity generation potential using industrial excess heat in the Swedish kraft pulp and paper industry?

The excess heat availability for six cases studies was obtained, with results presented through XHT signatures for two process integration cases. At temperatures $\geq 60^{\circ}\text{C}$, a total of 388 MW was found under theoretical assumptions of heat integration, and 457 MW if the current utility demands of the mills are estimated. The results also demonstrate that most of the available excess heat is present at temperatures below 60°C . It was shown that there is a total technical potential for 74–94 MW of installed capacity for electricity generation from low and medium temperature IEH using ORCs in the kraft pulp mills in Sweden. This would result in an increase in electricity generation in Swedish kraft mills of 10–13%.

RQ3: What are the effects of recovering industrial excess heat on the energy system in terms of global CO₂ emissions and economic aspects?

Directly estimating the costs for IEH recovery is an intensive process and even industries in the same sector have different process constraints and characteristics. By using specific investment costs from other studies analysing heat integration options in industrial processes, DH networks and technology costs, this thesis has shown that there is potential for IEH utilisation to be profitable under varying energy-market conditions. Under the right conditions, both direct heat deliveries and electricity generation using ORC technology are profitable investments. While DH deliveries can achieve higher profitability than electricity generation using ORCs, electricity generation is less sensitive to external conditions and was shown to be profitable in all the scenarios analysed. ORC systems are an established technology for IEH recovery, but the still relatively high investment costs for small-scale units results in lower economic feasibility. This issue is shown to be resolved with current economic incentives for renewable electricity production and avoided costs for industry by producing its own electricity. The analysed IEH recovery options showed potential for global CO₂ emission reductions when applying a systems perspective. Electricity generation from IEH was shown to have a greater potential for reducing global CO₂ emissions than DH deliveries, unless biomass is considered a limited resource. In a scenario with limited biomass availability, DH deliveries are more beneficial. The profitability of ORC electricity generation from IEH is lower than that of DH deliveries if investments in a heat-collection network are ignored and if DH deliveries are possible for more hours per year. IEH heat recovery using ORC cycles is better than implementing a small-scale ORC CHP plant in terms of profitability and achieving global CO₂ emission reductions. The realisation of the identified potential for IEH utilisation will depend on local conditions; for example, heat demand in a DH network is required for direct heat deliveries to be possible. Nevertheless, the option for electricity production from low and medium temperature sources that is made possible by the commercial deployment of ORC technology gives industry the flexibility to decide how to recover and use the available industrial excess heat.

8

Further work

The topic of industrial excess heat is an interesting one. From the work done for this thesis, a few ideas come to mind on how the several analyses made here can be improved and expanded. One interesting topic would be to apply the methods used here to evaluate the availability of IEH in other industrial sectors. A few case studies where process stream data are available are required.

The work regarding the pulp and paper sector in Sweden can be expanded by analysing the individual case studies more closely and including a geographical aspect. Trying to match the excess heat available with the heat demands in other industries and towns nearby is essential for increased IEH utilisation. This analysis would require a better understanding of how much of the heat could be delivered and for what period of the year.

One topic that was just considered as a background on Paper 3 is that the share of intermittent renewable energy will increase in the electricity generation matrix. This development will require solutions that provide dispatchable electricity generation, and the role of energy storage will also increase. One interesting development concerning IEH is studying how excess heat recovery, utilisation, and possibly storage can contribute to more flexible energy systems. Such analysis requires considering additional utilisation options and the introduction of dynamic aspects into the analysis.

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